ERDC/CHL TR-15-7

Coastal and Hydraulics Laboratory

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Hydraulic Evaluation of Culvert Valves at Eisenhower and Snell Locks, St. Lawrence Seaway

Richard L. Stockstill, E. Allen Hammack, David S. Smith, Carlos B. Bislip-Morales, Keith Green, and Jane M. Vaughan

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Final report

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Abstract

The aged, double-skin-plate valves of the Eisenhower and Snell Locks on the St. Lawrence Seaway are being replaced. The replacement valves are of the vertical-frame design to facilitate inspection and spot repair. A new vertical-frame valve was installed in the filling valve well of the Snell Lock's south-wall culvert. The new vertical-frame valve operated at a slower rate than the double-skin-plate valve, and its operation required more energy.

A physical model study was conducted to identify modifications that could be made to reduce the energy required to operate the new valve. The recommended valve design had a top plate that was only large enough to serve as a base for the stabilizers and strut connector. The bottom plate and bottom seal were replaced with a sharp-edged lip formed at the bottom end of the ribs and skin plate. The recommended valve was specifically designed to fit the Eisenhower and Snell Locks. This valve meets the USACE guidance for vertical-frame valves, and it has hoist forces that are lower than the valves currently in operation.

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Preface

The investigation reported herein was sponsored by the Saint Lawrence Seaway Development Corporation (SLSDC). This work was conducted in the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Research and Development Center (ERDC). Design and construction of the model and model experiments were conducted during the period of February 2012 to March 2014.

This research was conducted under the general direction of José E. Sánchez, Director of the CHL; Dr. William D. Martin, former Director of the CHL; Dr. Kevin M. Barry, Deputy Director, CHL; Dr. Jackie S. Pettway, Chief of the Navigation Division, CHL; Dr. Rose Kress, former Chief of the Navigation Division, CHL; Howard E. Park, acting Chief of the Navigation Branch, CHL; and Dr. Richard B. Styles, former Chief of the Navigation Branch, CHL. Thomas A. Lavigne, Director, Office of Engineering and Maintenance, SLSDC, and David A. Sanford, SLSDC, guided the study as it pertained to the replacement of the valves on the Eisenhower and Snell Locks. Lavigne and Sanford visited CHL to observe model operation, discuss test results, and determine the need for modifications in design to improve the hydraulic performance of the lock culvert valves.

The model components were constructed and assembled by Hugh F. Acuff III and Zachary S. Smith, Directorate of Public Works (DPW), ERDC, under the supervision of John E. Gullett, Chief of Model Shop, DPW. Machine work was provided by Christopher M. Ables under the supervision of Mickey D. Blackmon, Chief of the Machine Shop, DPW.

This investigation and subsequent report was completed by Dr. Richard L. Stockstill, E. Allen Hammack, David S. Smith, Carlos B. Bislip-Morales, Keith Green, and Jane M. Vaughan of the Navigation Branch, CHL. Acknowledgments are made to Thomas E. Hood, ERDC, who provided field experience and coordinated communications between SLSDC and CHL.

At the time of this report, LTC John T. Tucker III was the Acting Commander of ERDC. Dr. Jeffery P. Holland was Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	0.0254	meters
kips	4448.221	Newtons
miles (U.S. statute)	1.60947	kilometers
pounds (force)	4.44822	Newtons
pounds (force) per square inch	6894.7548	Newtons per square meters
tons (force)	8896.44	Newtons

1 Introduction

1.1 Project features

The St. Lawrence Seaway Development Corporation (SLSDC) is a wholly owned U.S. Government corporation within the U.S. Department of Transportation, which owns and operates that portion of the St. Lawrence Seaway in U.S. territorial waters between Lake Ontario and Montreal, Canada. The SLSDC's function is to facilitate the safe and efficient passage of commercial vessels through the Seaway. A major part of this function is the operation and maintenance of Dwight D. Eisenhower and Bertrand H. Snell Locks located in Massena, NY (Figure 1). Eisenhower and Snell Locks were constructed in the 1950s and were opened to deep draft navigation in 1959. Snell Lock is located approximately 3 miles downstream of the Eisenhower Lock, as shown in Figure 2.

Figure 1. Location of Eisenhower and Snell Locks.

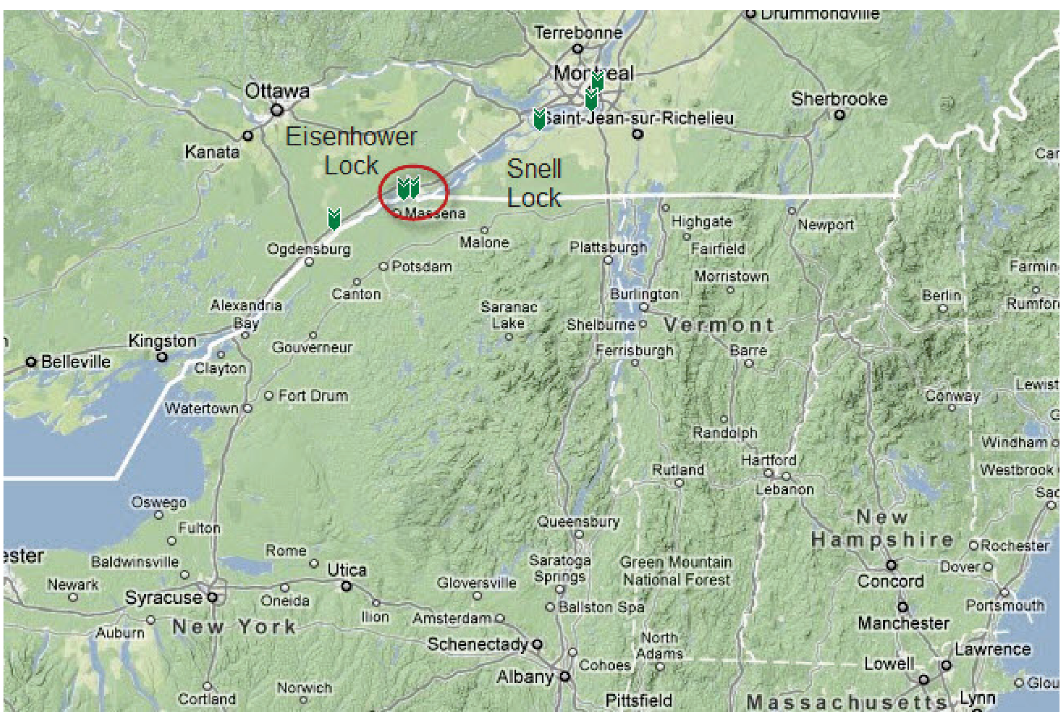
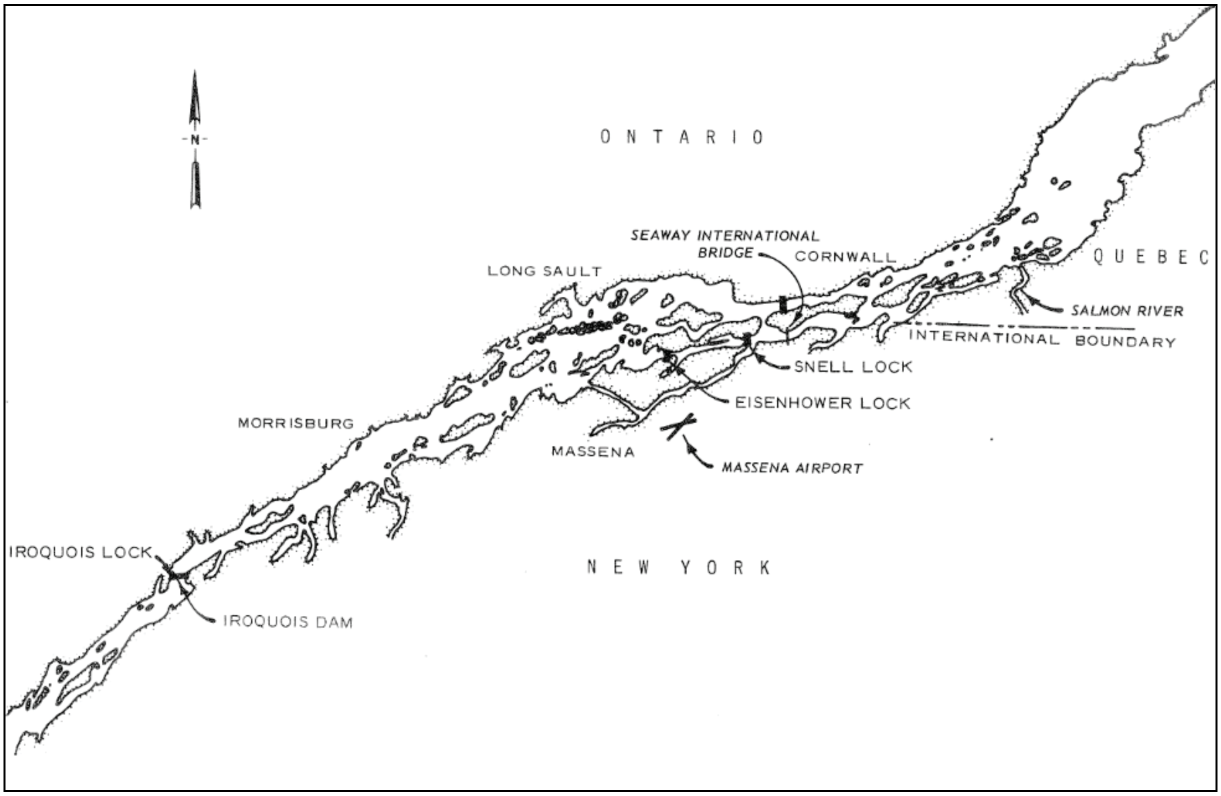


Figure 2. Saint Lawrence Seaway, Eisenhower and Snell Locks.



Both locks are 80 ft wide by 860 ft long (pintle to pintle). The Eisenhower Lock has a normal lift of 43 ft, and the Snell Lock has a normal lift of 49 ft. Flow through the lock culverts is regulated by reverse tainter valves operating in culverts that are 12 ft wide by 14 ft high (Figure 3). The existing culvert valves are of double-skin construction, but the SLSDC is in the process of replacing these valves with new valves of a vertically framed, single-skin design. The double-skin construction wraps structural members such that the valve is *streamlined* because fewer objects are exposed to the flow. However, maintenance is hindered due to lack of access to and inspection of the interior structural members. Although the single-skin design allows for inspection and spot repairs, each structural member can act as a flow obstruction and contribute to adverse loadings or vibration generated by shedding vortices. A photograph of two prototype valves is provided in Figure 4 in which a vertical-frame valve is in front of a double-skin-plate valve.

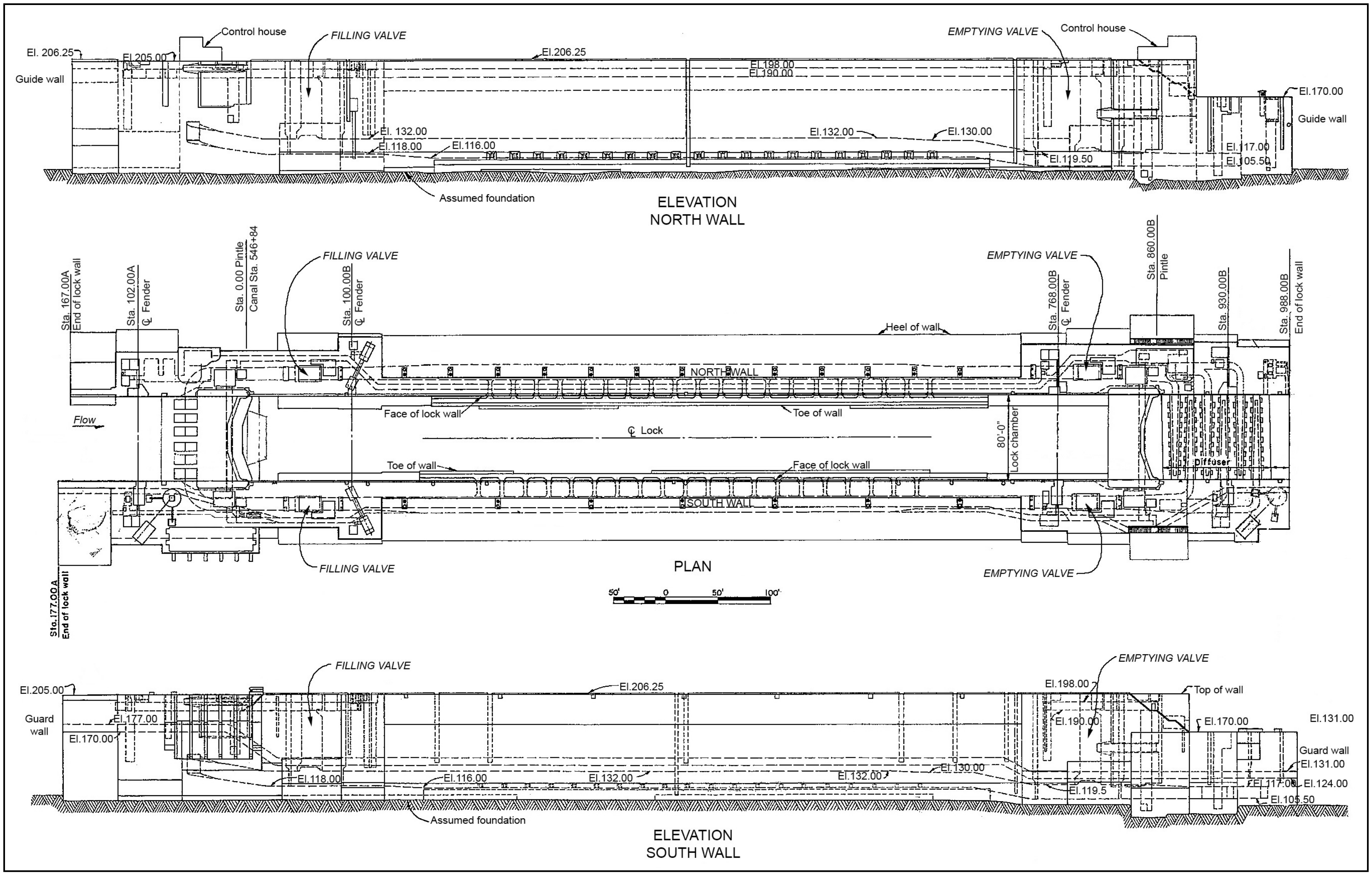


Figure 3. General plan and elevation of Snell Lock filling and emptying system.

Figure 4. Prototype valves, new vertical-frame valve in foreground and used double-skin-plate valve in background.

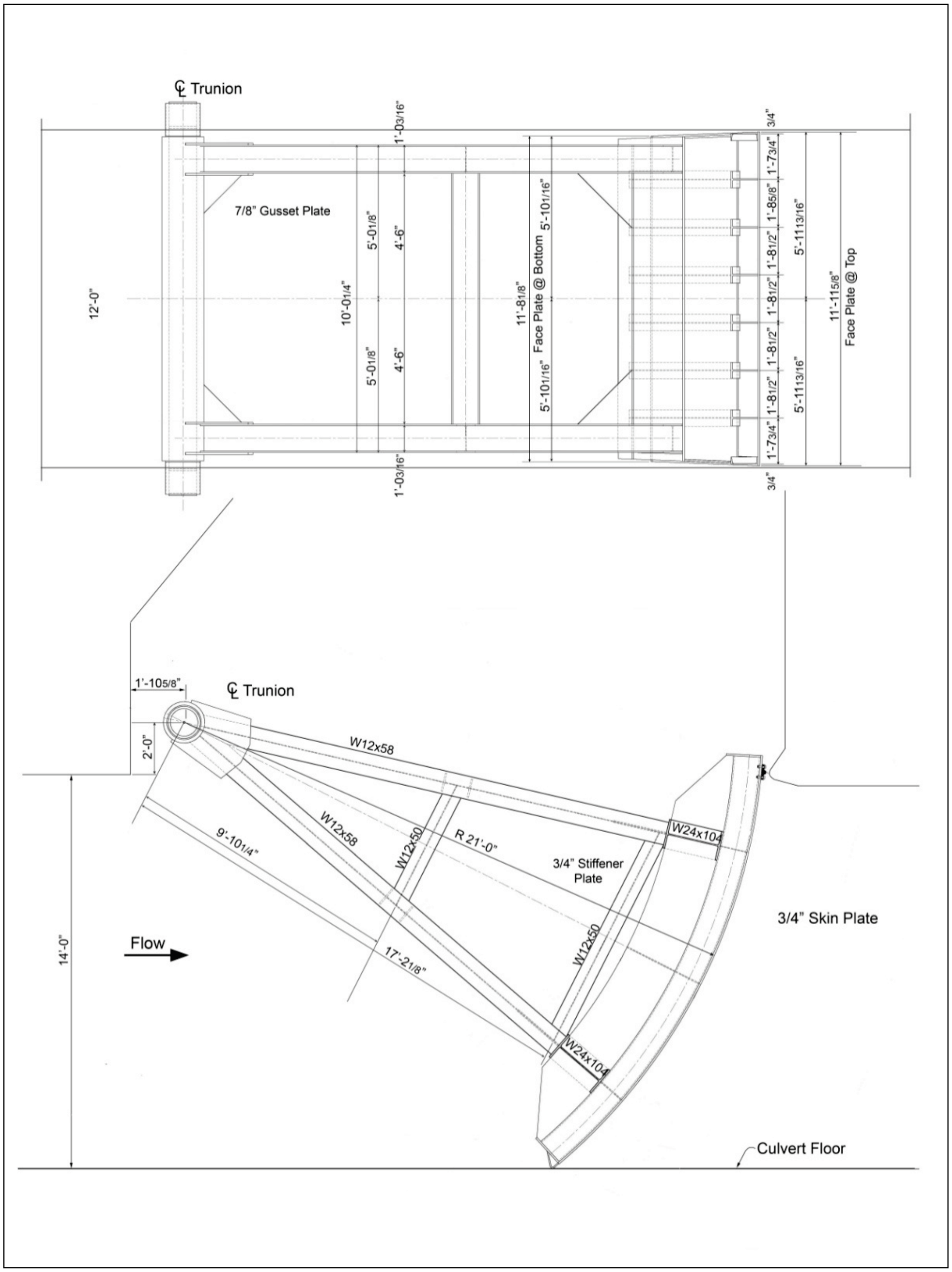
The filling and emptying systems of the Eisenhower and Snell Locks are essentially the same, with vertical intake manifolds in the upper sill serving a culvert in each wall and sidewall ports connecting the culvert to the lock chamber. The lock chamber is emptied by discharging through three laterals from each culvert located on the floor of the lower approach channel. There are four valves (two filling and two emptying) on each lock for a total of eight reverse tainter valves. Electro-mechanical operating machinery has been used to control valve movement. However, the electro-mechanical operating machinery at both locks is being replaced with oil hydraulic equipment.

The terms *valve stem*, *valve strut*, and *valve hoist mechanism* are synonyms for the steel structure that connects the mechanical operating equipment to the culvert valve. As-built drawings often use the term *strut* whereas operations personnel commonly use the word *stem*.

The new replacement reverse tainter valve, details of which are illustrated in the plan and elevation drawings in Figure 5, has a radius of 21 ft from the trunnion center to the downstream face of the valve's skin. The

trunnion pin is centered 2 ft above the culvert soffit. The valve seals at the top on the downstream side of the valve well. The trunnion block extends 1.89 ft out from the upstream valve well wall. Each end of the trunnion mount is in a 1.5 ft deep slot in either side wall. The slot allows installation and removal of the entire tainter valve.

Figure 5. Plan and elevation of the Type 1 (original) valve.



1.2 Problem

The existing culvert valves, illustrated on the “As Constructed” drawings from 1955, are of double-skin construction, but the SLSDC is in the process of replacing these valves with new valves of a vertically framed, single-skin design. Two valves of the new single-skin design were furnished to the SLSDC in January 2011, and one was installed in the south filling valve location at Snell Lock. An option for the SLSDC to order six more valves to complete the replacement was delayed because experience with the new single-skin valve currently in service revealed certain operational difficulty. Operation of the new valve exerted more load on the operating machinery than the double-skin-plate valve that it replaced. Hydraulic factors not anticipated in the design are suspected of affecting the valve.

A hydraulic model study was considered the most practical means to determine causes of the operational difficulties and to develop modifications to improve valve operating conditions.

1.3 Background on reverse tainter valves

The inventory of lock components and features listed in Pickett and Neilson (1988) shows that reverse tainter valves are the most common valve type found on major locks constructed by the U.S. Army Corps of Engineers (USACE). The reverse tainter valve differs from radial gates found on spillways in that the trunnion is upstream of the skin plate with the convex surface of the skin plate facing downstream and sealing against the downstream end of the valve well.

The USACE lock design manual, Engineer Manual (EM) 1110-2-1604 (Headquarters, USACE (HQUSACE) 2006), explains that there are three structurally different types of reverse tainter valves: horizontally framed, vertically framed, and double-skin plated. All three valve types can be made sufficiently rigid, but the vertical-frame and double-skin-plate valves are less susceptible to critical hydraulic loads and load variations during the opening cycle.

EM 1110-2-1610, *Hydraulic Design of Lock Culvert Valves* (HQUSACE 1975), states “for all three types of valves the two features that most affect loads on the valve hoist due to flowing water are the depth of the lower girder and the extension of the lower lip of the skin plate below the lower

girder. A decrease in the depth of the lower girder results in a decrease in peak downpull and load variations and a decrease in the range of valve positions at which uplift occurs. Data are not conclusive as to whether peak uplift is decreased. An increase in the extension of the lower lip of the valve below the lower girder decreases peak downpull and the range of valve positions at which downpull occurs but increases peak uplift and the range of valve positions at which uplift occurs. Load variations remain essentially unchanged."

The USACE-recommended valve is vertically framed with T-beams separating the skin plate from the main horizontal girders. This separation provides a passageway for flow circulation between the upstream face of the skin plate and the girders (Murphy and Ables 1965).

1.4 Prior model study

Physical model studies of various components of the Eisenhower and Snell Locks in the St. Lawrence Seaway project were conducted between 1954 and 1956 as part of the project's design process. The filling and emptying systems of the Eisenhower and Snell Locks were tested in a hydraulic model (U.S. Army Engineer District, St. Paul 1961). The lock model was constructed to a scale of one unit of prototype length equaled 24.24 units of model length (1:24.24). All the essential features of the lock filling and emptying system were included. The model reproduced approximately 200 ft of the upstream approach; the entire system including intakes, reverse tainter valves and culverts; side-wall-port manifold system; outlets; and approximately 300 ft of the downstream approach. The study reported filling and emptying curves which include valve schedule, rate-of-rise (rate-of-fall), and operation time; vortex tendencies at the intakes; hawser forces on ships moored in the chamber; and pressures throughout the culvert system. Data presented in U.S. Army Engineer District, St. Paul (1961) were used in the current valve study to determine the valve position versus discharge during lock operations.

1.5 Purpose and scope

The purpose of this study was to determine the reason for the lock operation problems with the new valve and to develop modifications that would allow more efficient operation. An in-depth study of the hydraulic characteristics of the single-skin culvert valve design was conducted using a physical hydraulic model. The study evaluated hoist forces under anticipated conditions of operating head and discharge.

2 The Model

2.1 Description

The lock culvert valve was modeled at a scale of 1:15 in a test facility (Figure 6) that reproduced the valve, valve well, bulkhead slots, and approximately 75 ft of culvert above and 175 ft below the valve. The upper pool was represented with a pressure tank. Culvert pressure was regulated with a slide gate located near the end of the culvert. The valve well, bulkhead slots, and culvert were constructed of transparent plastic to permit observation of flow (Figure 7 and Figure 8). The valve (Figure 9) was fabricated of brass and reproduced the prototype tainter valve to scale in size and shape. Side seals were not installed on the valve as this would create excess friction between the valve and the culvert walls in the model and could damp vibration tendencies.

Water was supplied to the model through a circulating system in which discharge was measured using a standard orifice meter in the supply line upstream of the model. The culvert consisted of a section of 12 in. pipe containing the orifice plate, a transition to the rectangular culvert, two bulkhead slots (upstream and downstream), a valve well, and a flow control gate at the downstream end of the model.

A sketch showing how the valve and struts are positioned in the valve well is provided in Figure 10. The lifting mechanism included two struts (one long and one short) which were fabricated from steel and brass rods. The bottom of the long strut was connected to a lift pin on top of the valve, and the top was connected to the short strut. The top of the short strut was connected to an arm which was rotated with a wench. This rotation and subsequent motion of the strut valve linkage mimicked the prototype valve lifting mechanism.

2.1.1 Instrumentation

Dynamic forces on the valve strut (hoist loads) were measured with a commercial load cell mounted as an integral section of the strut (Figure 11). The load cell was of an S-beam form factor, a 50 lb capacity, and a 1.0 mV/V output. The hoist loads were measured at a rate of 50 Hz. The average loads and maximum and minimum instantaneous loads on the valve hoisting mechanism were determined from the time-varying data.

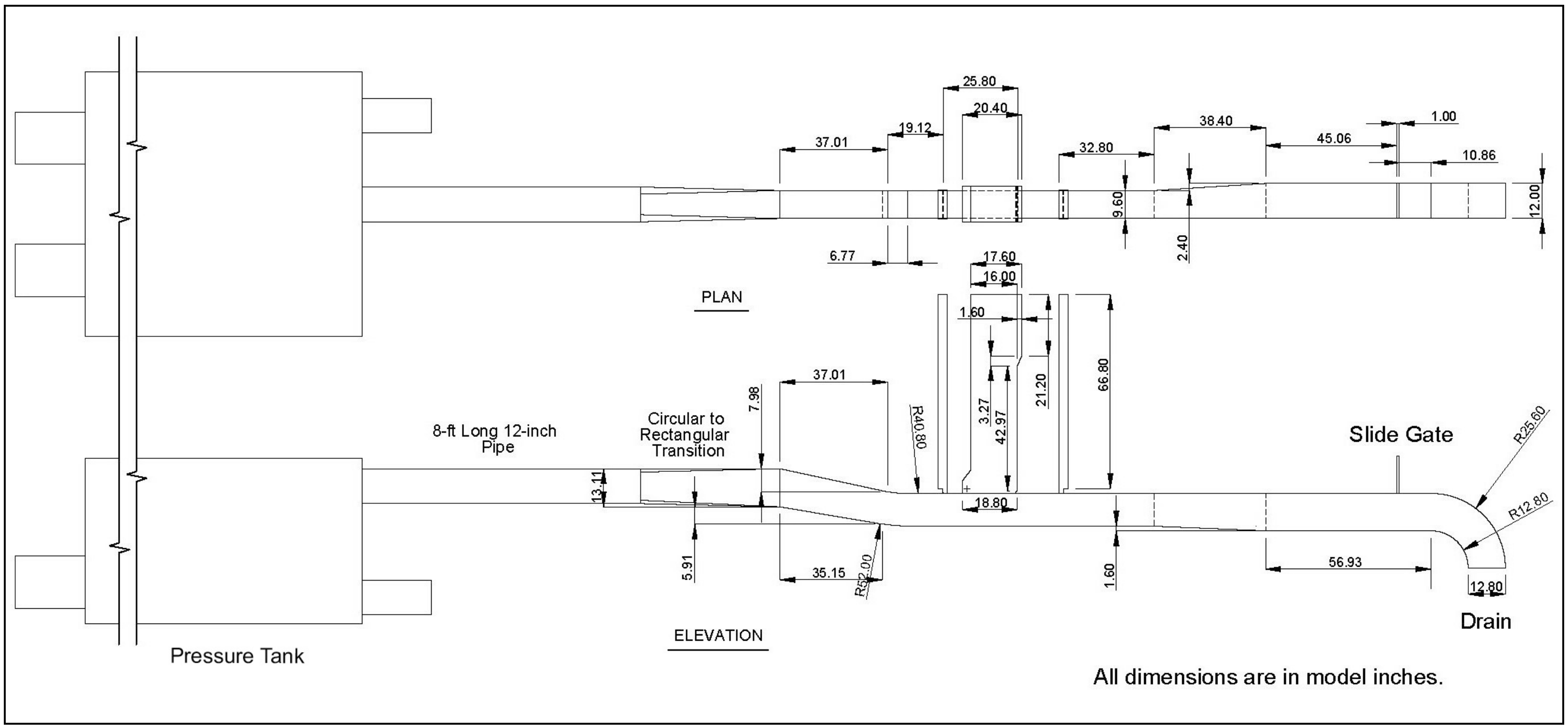


Figure 6. Physical model layout.

Figure 7. Dry bed view of the 1:15-scale model looking downstream.

Figure 8. Dry bed view of the 1:15-scale model looking upstream.

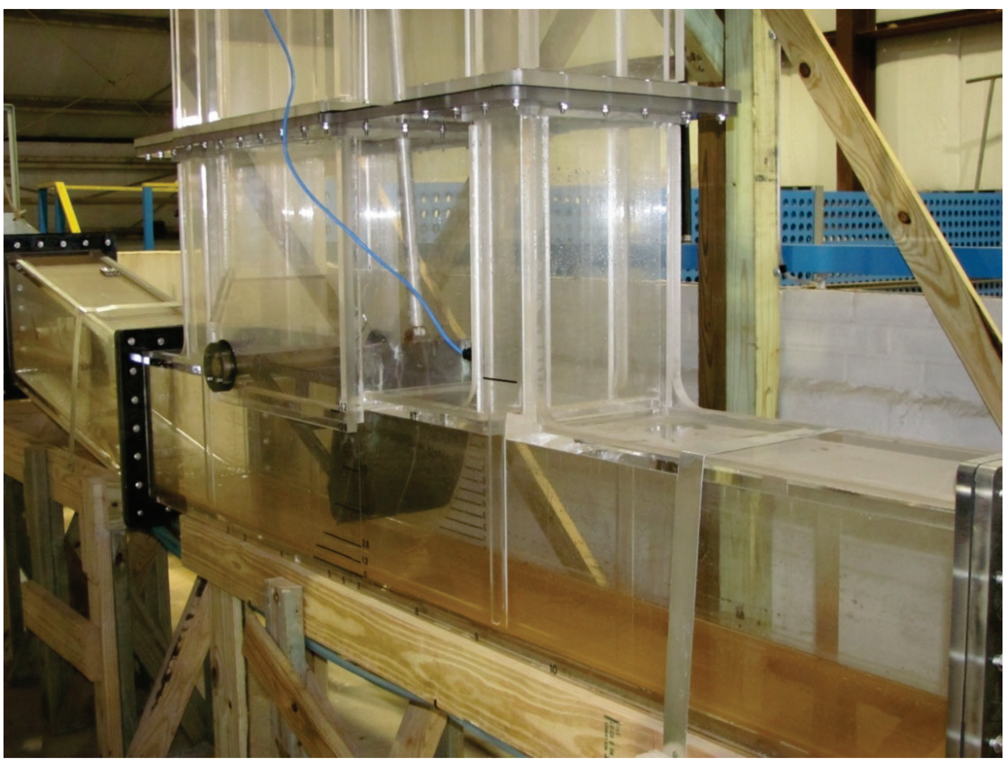
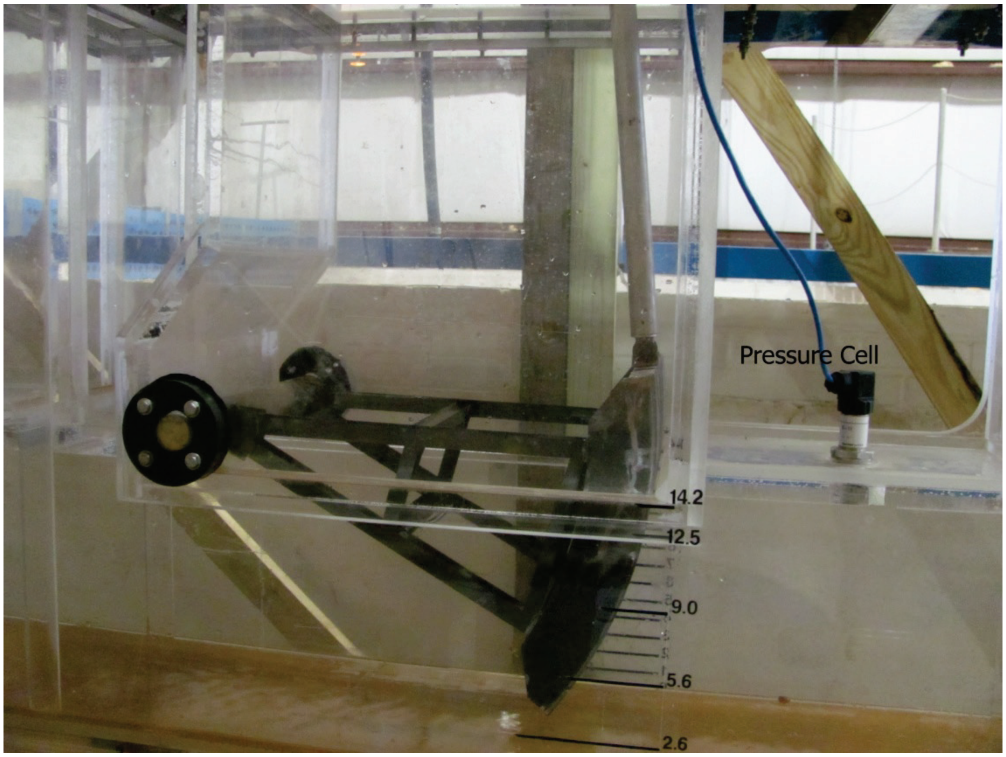


Figure 9. Close-up view of test section and model valve; flow is from left to right.



Toward the end of the study, trunnion forces on two of the valve designs were measured. A commercial load arm (Figure 12), which measured two normal components of the force placed on it, was used to obtain the horizontal and vertical components and the resultant force acting on each trunnion. The trunnion force instrument had eight, small strain gages (four for each bi-axial force component) affixed to the arm. The commercial load arm was rated for a maximum load of 200 lb and a nominal output of 3.0 mV/V. The data acquisition system was tuned such that the amplifiers' output range was scaled over a smaller load range.

The load arm was calibrated in the dry where the only force on the trunnion was due to the valve's weight. The valve was rotated to a known angle, and both the vertical and horizontal components were calibrated to calculated reaction force values. The load arm gage was calibrated at two valve positions. The trunnion force instrument was submerged during the experiments and thus required water proofing. Dielectric grease was used along with o-ring seals in the bushings to prevent the instrument from being damaged. Upon completion of data collection, the model was dewatered, and the calibration values were confirmed.

Figure 10. Valve machinery, Snell Lock filling valve.

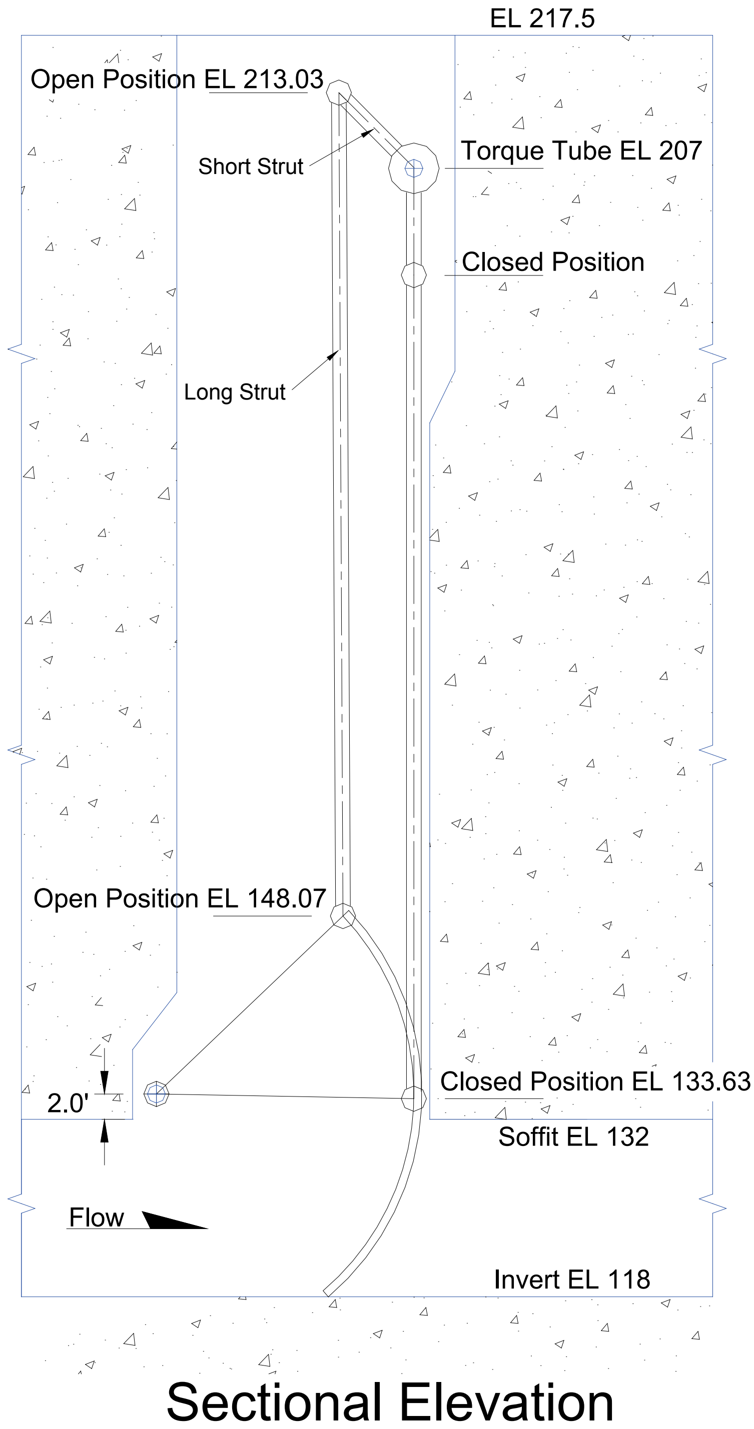
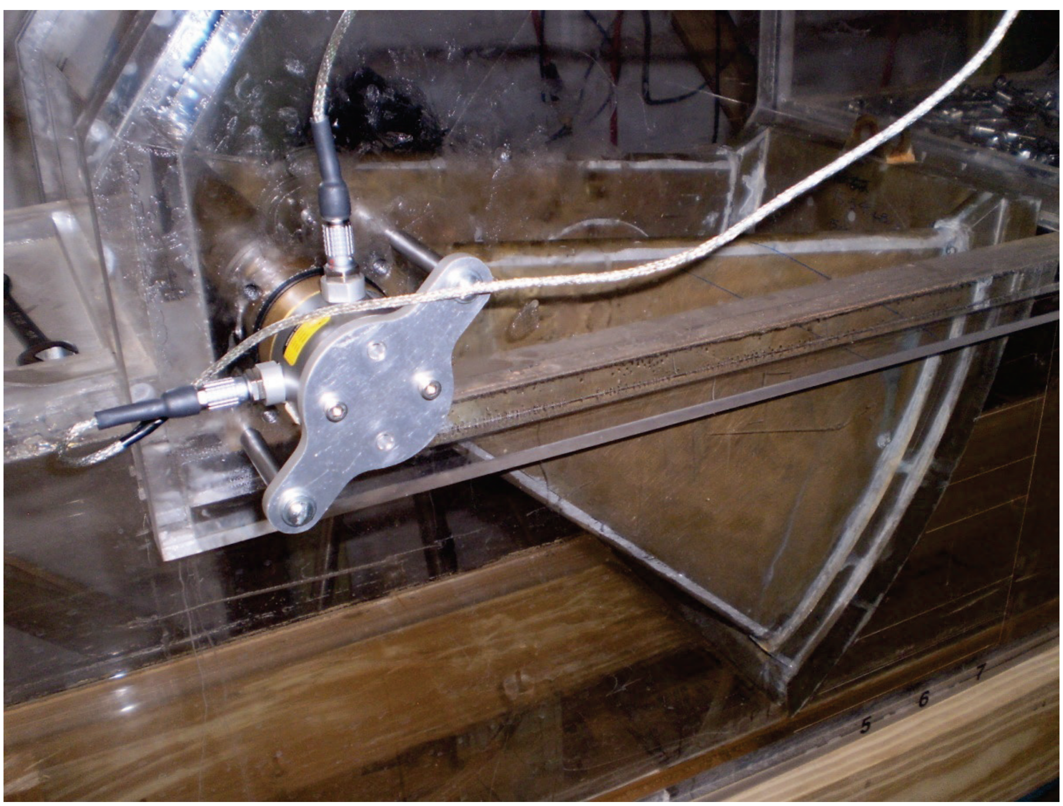


Figure 11. Load cell and strut prior to assembly.

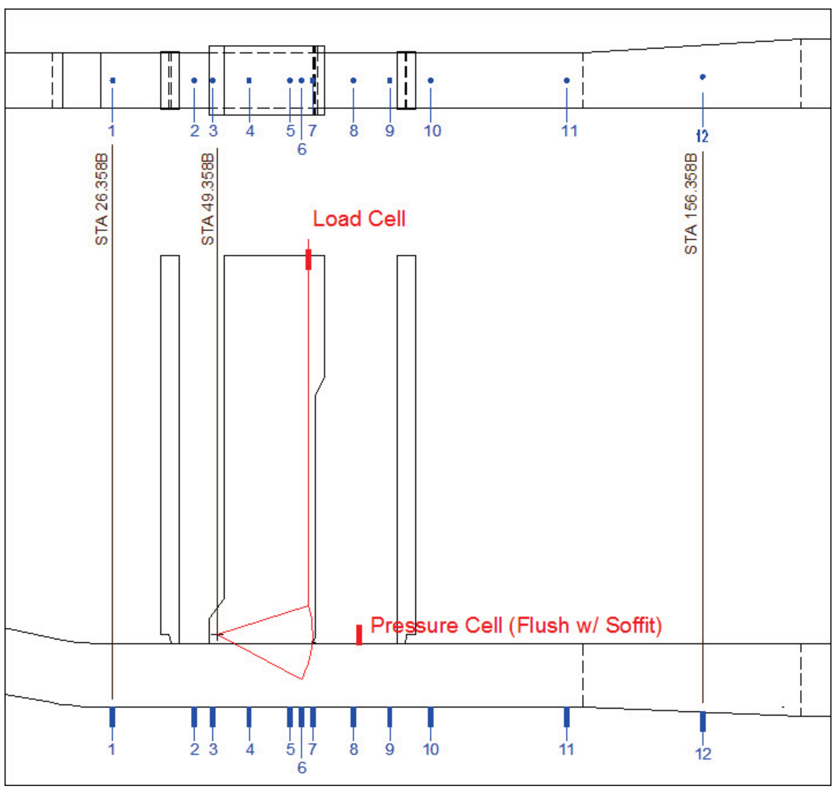
Figure 12. Trunnion load arm.



The dynamic trunnion force data were sampled at a frequency of 50 Hz. The average and instantaneous maximum and minimum horizontal and vertical component of forces on each trunnion were then determined from the data.

Piezometers were used to determine average pressures throughout the model. The rapidly fluctuating pressures downstream of the valve were measured with a commercial pressure cell flush mounted on the culvert soffit. Locations of the piezometers and pressure cell are illustrated in Figure 13. The stations and elevations of the piezometers are given with the pressure data in tables (e.g., Table 3). Piezometers were connected to glass open-air manometers arranged on a board for convenience of viewing.

Figure 13. Location of piezometers, pressure cell, and hoist load cell.



The pressure transducer was located 8.3 ft (0.6 culvert heights) downstream of the valve. Its sensing diaphragm was flush with the interior upper surface of the culvert to allow pressure measurements without disturbing the flow. The transducer had a 1 in. diameter and a measurement range of 0 to 5 psi with an output of 4–20 mA. As with the other transducers connected to the data acquisition system, pressure transducer data were recorded at a sampling frequency of 50 Hz.

2.1.2 Model construction

Three-dimensional (3D) CAD models of the valve and culvert were constructed from as-built line drawings of the locks. The CAD models were scaled to model dimensions and used to create shop drawings.

All culvert walls and the downstream gate were constructed of three-fourth in. acrylic. This material choice allowed for the flow to be observed during model operation while being strong enough to withstand both the model weight and the weight of the water. The culvert sections were fastened together, and gasket material was placed in each flanged section to prevent leaks. The valve well flanges allowed the model to be disassembled so the different valve types could be installed more easily.

The reverse tainter valves were constructed of brass. Components of the 3D CAD valve models were cut from a sheet of brass using a computer-operated water jet. These components were then soldered together to form the completed valve. The valve lip was constructed of plastic with a 3D printer and fastened to the bottom plate.

2.2 Similitude considerations

2.2.1 Kinematic similitude

Kinematic similarity is an appropriate method of modeling gravity-driven flows in which the viscous forces are negligible. Kinematic similitude requires that the ratio of inertial forces ($\rho V^2 L^2$) to gravitational forces ($\rho g L^3$) in the model is equal to those of the prototype. This ratio is generally expressed as the Froude number, N_F,

$$N_F = \frac{V}{\sqrt{gL}} \tag{1}$$

where:

ρ = fluid density
V = fluid velocity
L = a characteristic length
g = acceleration due to gravity.

The characteristic length, L, is usually taken as the flow depth in open-channel flow.

2.2.2 Dynamic similitude

Modeling of forces is the primary purpose of the laboratory investigation. Appropriate scaling of viscous forces requires the model be dynamically similar to the prototype. Dynamic similarity is accomplished when the ratios of the inertia forces to viscous forces (μVL) of the model and prototype are equal. Here, μ is the fluid viscosity. This ratio of inertia to viscous forces is usually expressed as the Reynolds number, N_R,

$$N_R = \frac{VL}{\nu} \tag{2}$$

Here:

ν = kinematic viscosity of the fluid ($\nu = \mu/\rho$).

In pressure flow analysis, the pipe hydraulic diameter is usually chosen as the characteristic length, L.

Kinematic similitude, combined with Reynolds numbers large enough to result in negligible viscous effects, accurately reproduces streamlines and, therefore, the fluid accelerations and hydrodynamic forces. Viscous effects that may affect the forces on the valve are flow separation points and reattachment locations. These flow features produce zones of low pressure on the backside of flow obstructions such as a partially opened valve protruding into the flow. Since the point of flow separation is fixed at the lower lip of the valve for all flow conditions, viscous effects are independent of scale and velocity (Baines 1954).

Equating the model and prototype Froude numbers yields the following relations between the dimensions and hydraulic quantities shown in the following tabulation (Table 1).

These relations are used to convert between model data and prototype equivalents.

Table 1. Relations between the dimensions and hydraulic quantities.

Characteristic	Dimension*	Scale Relation Model: Prototype
Length	$L_r = L$	1:15
Area	$A_r = L_r^2$	1:225
Time	$T_r = L_r^{1/2}$	1:3.8730
Velocity	$V_r = L_r^{1/2}$	1:3.8730
Discharge	$Q_r = L_r^{5/2}$	1:871.421
Force	$F_r = L_r^3$	1:3375
Pressure	$P_r = L_r$	1:15

*Dimensions are in terms of length.

2.3 Experimental procedures

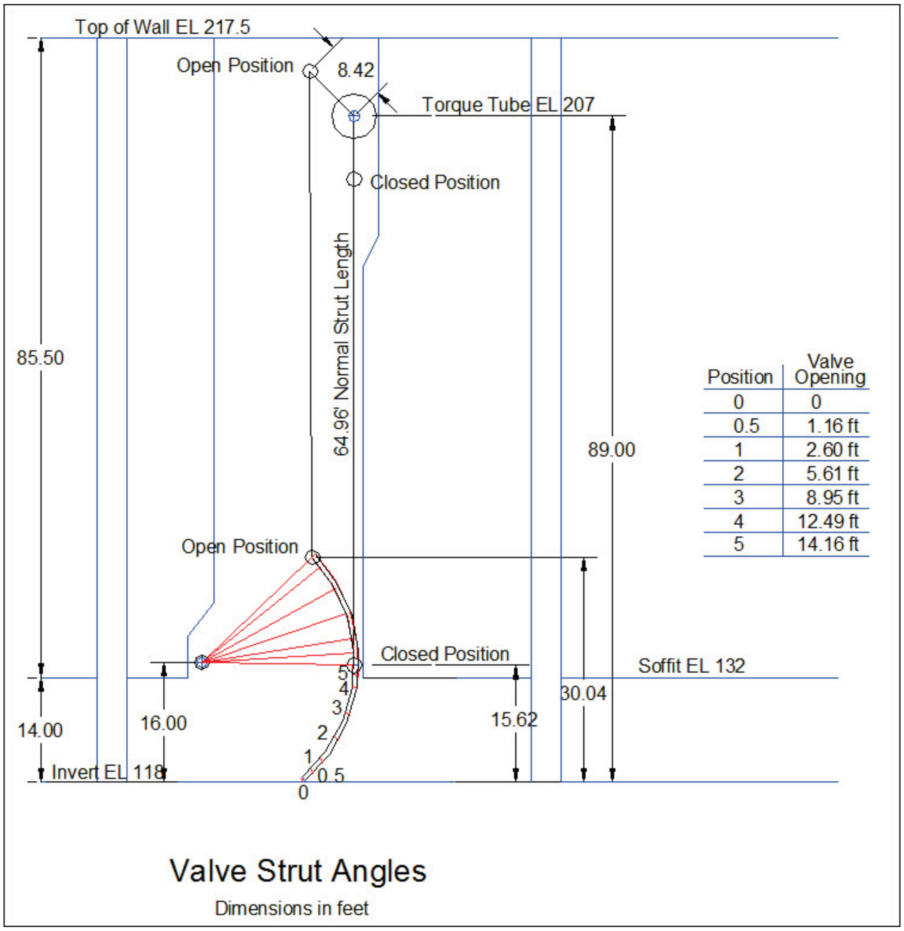
2.3.1 Operation

The lock culvert valve was tested for various valve openings with the design lift of 49 ft. The elevations of the Snell Lock were used because this lock has a higher design lift. A filling valve was represented because the filling valves have less submergence (higher invert) than the emptying valves. Less submergence leads to lower average pressures and larger pressure variations in the zone downstream of the valve. The recommended valve design will be used for all eight replacement valves on the Eisenhower and Snell Locks.

Experiments were conducted with the valve at fixed positions and under several steady-flow conditions. Steady-flow tests simulate the conditions occurring at a particular instance during a lock operation. Each experiment maintained the energy grade line upstream from the valve (Piezometer 1, Figure 13) at approximately 82 ft above the floor of the culvert (el 200.0[1] in the Snell Lock filling valve) with a manually operated control gate located near the end of the culvert (slide gate in Figure 6). El 200.0 is normal pool elevation at the Snell Lock. The valve positions, which are shown in Figure 14, corresponded to those used by the SLSDC for design and evaluation calculations. For each valve position, hoist load data were measured at discharges selected to envelope normal prototype operating conditions.

[1] All elevations (el) cited herein are in feet above mean sea level, U.S. Lake Survey Datum, 1935 adjustment.

Figure 14. Valve positions; elevations are from the Snell Lock filling valve.



The time-varying forces on the hoisting mechanism and pressures at the culvert soffit downstream of the valve were measured simultaneously. Each experiment consisted of three sets of data recorded for a period of 180 sec (model). Piezometric elevations were also recorded as part of each experiment.

2.3.2 Flow conditions

Each steady-state flow setup represented a head/discharge condition expected to occur during normal filling operations. Fill valve head/discharge information for a 4 min valve operation is given in the physical model study reported by U.S. Army Engineer District, St. Paul (1961). However, the Eisenhower and Snell Locks use 2 min valve operations for both filling and emptying the locks. The current study required a means to estimate the discharge that the prototype experiences with each valve position during a 2 min valve filling operation.

Head/discharge relations with a 2 min filling valve operation were computed using the numerical flow model LOCKSIM (Schohl 1999) in a manner similar to that described by Stockstill (2002). A numerical model of the Snell Lock filling system was constructed to compute conditions with various operational schemes. The numerical model reproduced the entire filling system, including the intakes, valves, valve wells, culverts, side wall port manifolds, and lock chamber. Discharge and piezometric head in the culvert and free-surface channel components were computed by numerically solving partial differential equations for one-dimensional unsteady flow. LOCKSIM couples the unsteady pressure-flow equations, which are applicable to the conduits within the system, with the free-surface equations describing the approach reservoirs, valve wells, and lock chamber flows. LOCKSIM simulates closed-conduit components such as culverts, reverse tainter valves, pipe losses, tees, and manifolds.

Physical model data were used to quantify energy loss coefficients of the lock system. The idea was to construct a model of the Snell Lock filling system, validate the model with physical model data for a 4 min valve filling operation (U.S. Army Engineer District, St. Paul 1961), and then compute the hydraulic conditions associated with a 2 min valve filling operation. The conditions were an upper pool of el 200, a lower pool of el 151, and a 4 min valve opening as shown in Figure 15. The results of the adjusted model are shown on the time variation of the lock chamber water-surface elevation during filling presented in Figure 16. The numerical model results compared with those reported in the physical model study are also illustrated in Figure 16. The numerical model closely reproduced the physical model data, aside from the fact that the numerical model filled a little too fast during the third minute of operation, in which the computed water-surface elevation was higher than the measured valves. However, the numerical model accurately reproduced the fill time of 8.4 min.

The validated model was then used to compute the valve rating for a 2 min filling valve operation. The model was changed from a 4 min to a 2 min valve operation time (Figure 15). The resulting 2 min valve discharge rating curve with a 49 ft lift is shown in Figure 17. Figure 15 shows the valve opening rate, and Figure 17 shows the discharge variation as the valve opens. The curved tainter shape results in a parabolic valve opening when the hoist motion is linear. So, given a constant hoist motion, the valve opening rate begins relatively slowly and increases as the valve operation continues. The variable valve opening rate is illustrated on the valve operation schedules in Figure 15.

Figure 15. Lock culvert valve operation schedules.

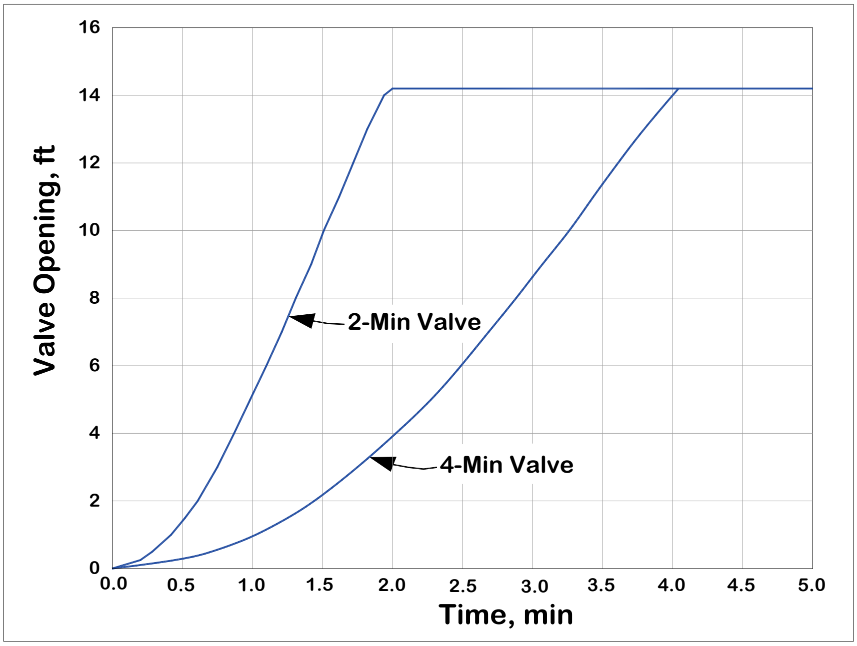


Figure 16. Snell Lock filling curve; physical model data from U.S. Army Engineer District, St. Paul (1961).

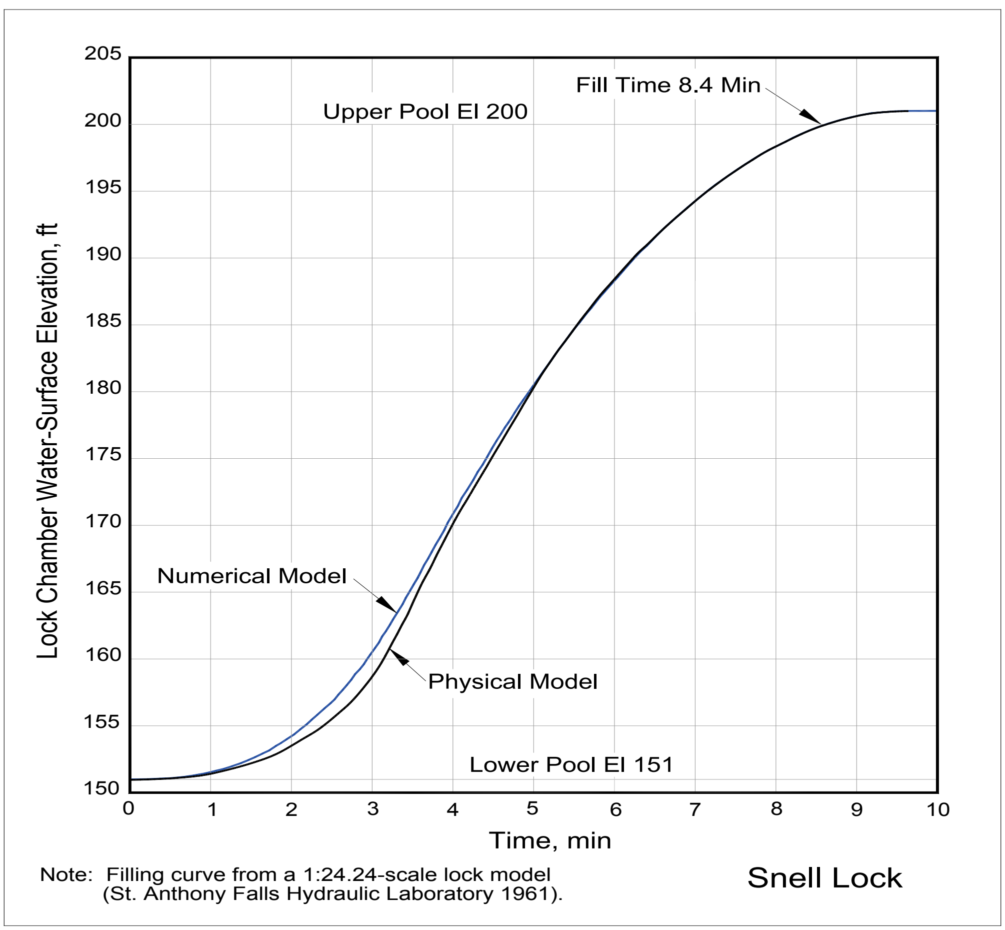
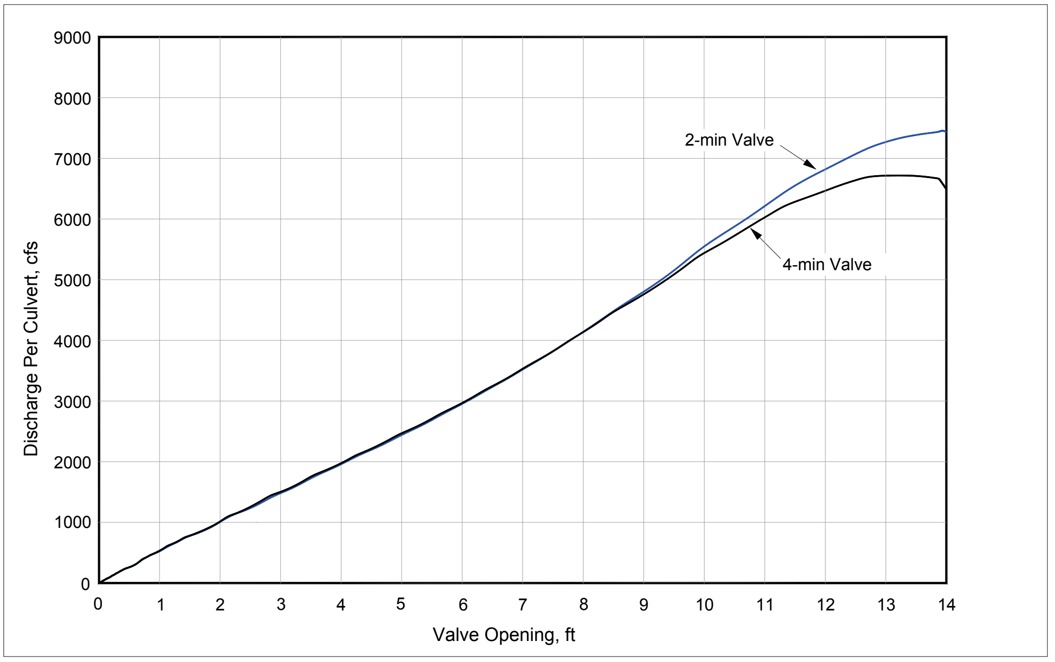


Figure 17. Discharge rating curves, 49 ft lift.



The discharges calculated using the LOCKSIM model were set in the 1:15-scale valve model, while a total head (piezometric elevation plus velocity head) of el 200 was set in the culvert at the upstream end of the model.

2.4 Presentation of data

The valve size and shape were reproduced in brass to represent the steel material of the prototype. While the web and flange width of each girder, T-beam, and other structural components were carefully scaled, the thickness of some members was too thin to scale exactly. So the model weight was not an exact reproduction of the prototype weights that were provided by the SLSDC. Addition or removal of weight would require modification of the valve's geometry and perhaps a shifting of the valve's center of gravity. Both the geometry and center of gravity are important parameters, so the constructed model valve geometries were not altered. Instead, corrections were made to the reported hoist loads. Since the geometry of the valve and flow patterns resulting from the fluid interacting with the valve were also accurately represented (kinematic similitude), the hydraulic loads were accurate. The hydraulic forces are the sum of hydrostatic and hydrodynamic forces due to accelerations as flow passes the valve.

The hydraulic load was calculated as the difference in the hoist load measured with flowing water and the hoist load measured in the dry

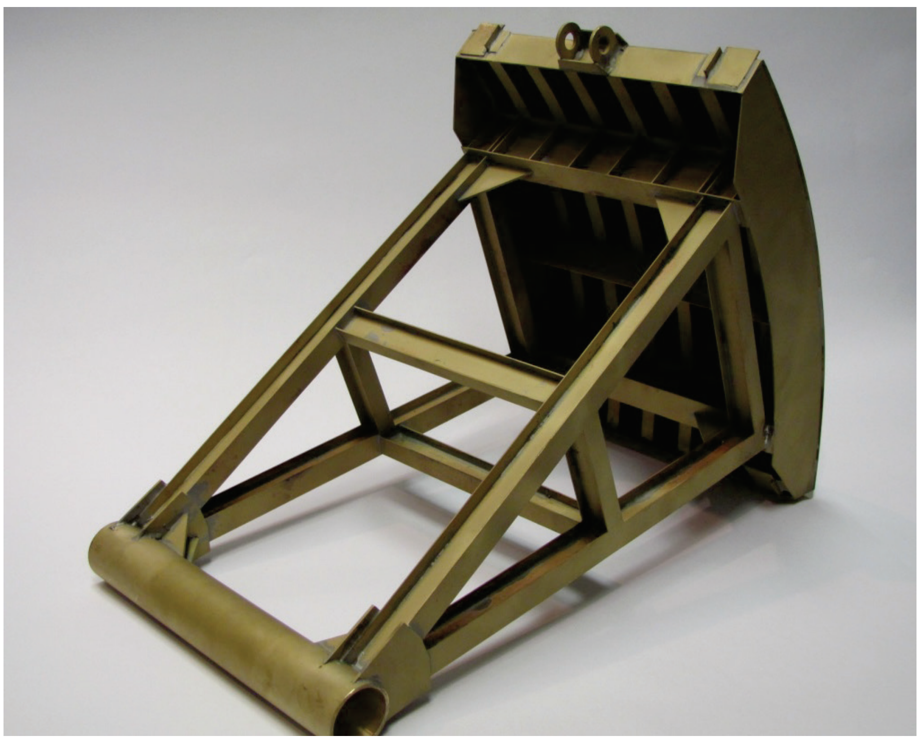
model. A weight correction factor was determined as the ratio of the prototype valve weight to the scaled weight of the model valve. The dry hoist loads were multiplied by the weight correction factor, and then the corrected hoist loads were computed as the sum of the corrected dry hoist loads and the hydraulic loads. These corrections were applied to each test condition with each valve design. The vertical-frame model valve was only 2% lighter than the prototype (weight correction factor of 1.02). However, the double-skin-plate model valve's scaled weight was heavier than the prototype equivalent such that the weight correction factor was 0.89. The hoist loads given in this report have been corrected to reflect the differences between scaled model and prototype valve weights.

3 Model experiments

3.1 Type 1 (original) valve

The Type 1 (original) valve was of the vertical-frame design that replaced one of the existing double-skin-plate valves. The current study was initiated because the Type 1 valve required more energy to operate and operated at a slower rate than the double-skin-plate valve that it replaced. A photograph of the prototype valves is provided in Figure 4, in which the Type 1 valve is the vertical-frame valve in the foreground and the double-skin-plate valve is behind it. The Type 1 model valve is shown in Figure 18.

Figure 18. 1:15-scale model of Type 1 (original) valve.



Details of the Type 1 valve and its position relative to the culvert and valve well are shown in Figure 5. Each valve tested had a radius of 21 ft. The trunnion arms were W12 × 58 steel members. The web was made of WT12 × 31 wide-flange-tee steel members and a three-fourths in. thick skin plate was mounted on the downstream side of the ribs. Two horizontal W24 × 104 steel wide-flange girders were mounted horizontally to the trunnion arms just upstream of the web members. One one-half in. and two three-

eighths in. thick steel plates were placed laterally across and between the ribs to act as stiffener plates.

Hoist-load data obtained in the model of the Type 1 (original) valve are presented in Table 2. The maximum and minimum loads on the hoist for the discharges corresponding to the 2 min valve schedule are plotted in Figure 19. Where hoist-load values are greater than the load due to the valve's dry hoist load, hydraulic forces were acting to close the valve; where they are less, hydraulic forces were acting to open the valve. The largest average hoist loads were 38.1 kips at a 5.6 ft opening and 38.6 kips at a 9.0 ft valve opening. Load fluctuations are illustrated in the maximum variations in total hoist load plot in Figure 20. The maximum fluctuations in hoist load were found to occur at the large valve openings. In some cases, the fluctuating forces were large enough to cause load reversals. For example, at a 12.5 ft valve opening and 2 min valve schedule, the hydraulic load varied 15.8 kips from 1.4 kips downpull to 14.4 kips uplift. The hydraulic forces with a 2 min valve schedule are presented in Figure 21. The largest hydraulic force, 8.9 kips of uplift, occurred at the full-open position.

Table 2. Hoist loads, Type 1 (original) valve.

Valve Opening, ft	Dry Valve Load, kips	Culvert Discharge, cfs	Total Hoist Load, kips		
			Minimum	Maximum	Observed Average
1.2	30.4	630	25.3	26.0	25.6
		730	28.1	29.5	28.7
		910	28.8	30.1	29.3
		1,090	30.6	32.3	31.3
2.6	31.2	1,240	30.5	32.1	31.2
		1,280	31.0	32.3	31.6
		1,550	32.9	34.7	33.8
		1,860	36.1	38.9	37.3
5.6	32.8	1,820	30.0	32.3	31.0
		2,270	31.8	34.8	32.9
		2,730	34.1	37.7	35.8
		2,740	36.7	39.8	38.1
9.0	34.8	2,570	30.4	33.3	31.5
		3,210	30.8	34.1	32.4
		3,850	31.7	35.8	33.8
		4,770	35.0	41.9	38.6

Valve Opening, ft	Dry Valve Load, kips	Culvert Discharge, cfs	Total Hoist Load, kips		
			Minimum	Maximum	Observed Average
12.5	38.3	3,330	30.4	34.0	32.4
		4,160	30.2	34.9	32.4
		5,000	28.8	36.0	32.5
		6,640	38.2	43.2	40.7
		7,090	23.9	39.7	32.3
14.2	40.8	4,020	32.4	36.0	34.2
		5,030	27.1	37.5	32.8
		6,040	23.7	37.9	32.1
		6,490	26.5	37.3	32.3
		7,040	28.8	35.5	32.7
		7,440	24.3	38.2	31.9

Figure 19. Hoist load, Type 1 (original) valve, 2 min valve schedule.

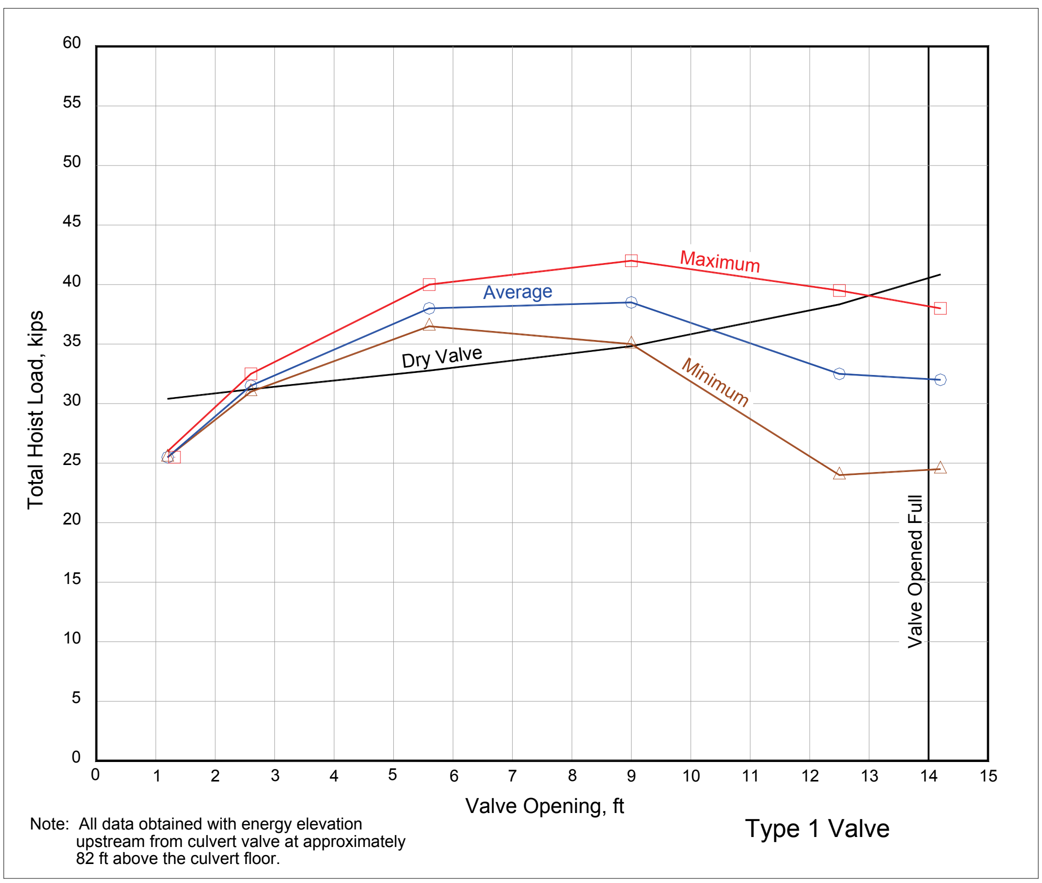


Figure 20. Maximum variation in total hoist load, Type 1 (original) valve, 2 min valve schedule.

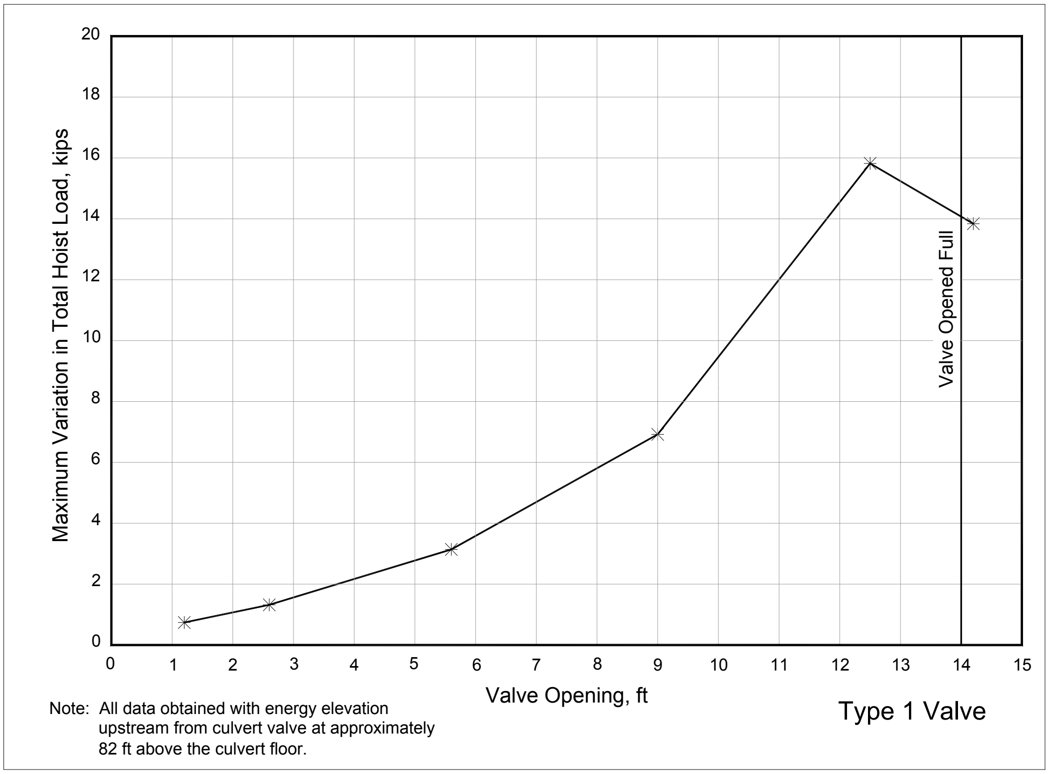
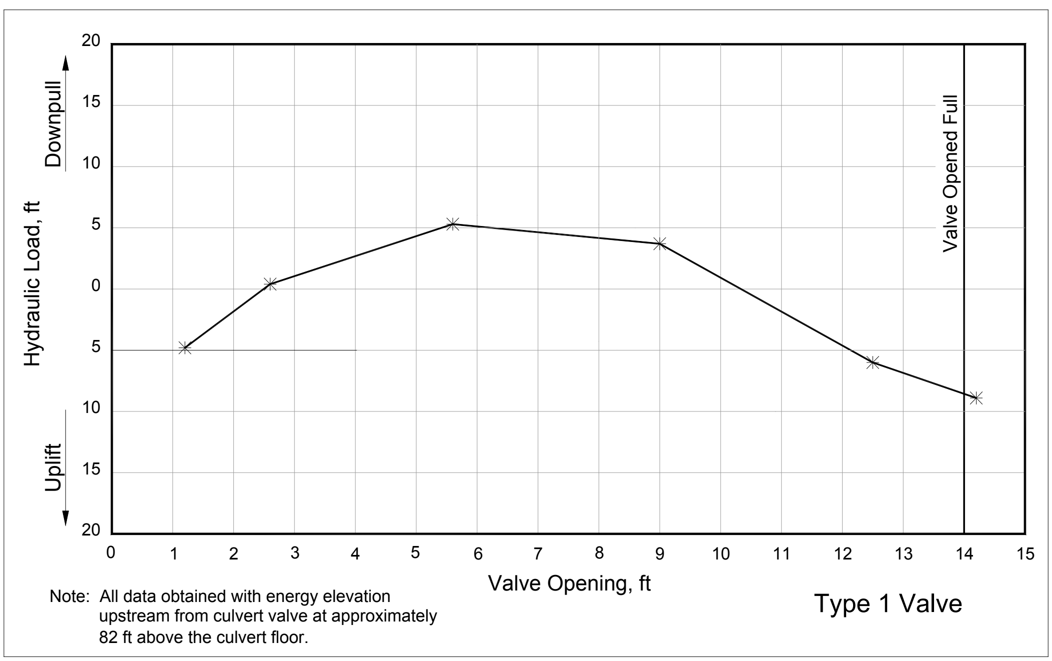


Figure 21. Hydraulic load, Type 1 (original) valve, 2 min valve schedule.



Pressures measured in the culvert with flow conditions associated with a 2 min valve schedule are presented in Table 3. Locations of the piezometers and the pressure cell are shown in Figure 13. The pressure cell was located

Table 3. Pressures in culvert, Type 1 (original) valve (Snell Lock), 2 min valve schedule.

Valve Opening, ft	Discharge, cfs	Piezometer			Pressure		
		Number	Station	Elevation	Minimum	Maximum	Observed Average
1.2	630	1	0+20B	118.0	199.8	199.8	199.8
		2	0+38B	118.0	199.8	199.8	199.8
		3	0+42B	118.0	199.8	199.7	199.8
		4	0+50B	118.0	199.7	199.7	199.7
		5	0+59B	118.0	194.9	194.9	194.9
		6	0+61.5B	118.0	194.3	194.3	194.3
		7	0+64B	118.0	194.1	194.1	194.1
		8	0+73B	118.0	194.0	193.9	194.0
		9	0+81B	118.0	194.0	193.9	194.0
		10	0+90B	118.0	194.0	194.0	194.0
		11	1+20B	118.0	194.8	194.8	194.8
		12	1+50B	116.8	194.8	194.8	194.8
2.6	1280	1	0+20B	118.0	199.1	198.9	199.0
		2	0+38B	118.0	199.2	198.9	199.1
		3	0+42B	118.0	199.1	198.9	199.0
		4	0+50B	118.0	199.0	198.9	199.0
		5	0+59B	118.0	196.8	196.5	196.7
		6	0+61.5B	118.0	195.0	194.9	195.0
		7	0+64B	118.0	194.6	194.2	194.4
		8	0+73B	118.0	194.3	194.0	194.2
		9	0+81B	118.0	194.2	194.0	194.1
		10	0+90B	118.0	194.2	194.0	194.1
		11	1+20B	118.0	195.2	195.0	195.1
		12	1+50B	116.8	195.5	195.2	195.4
5.6	2740	1	0+20B	118.0	196.3	195.3	195.8
		2	0+38B	118.0	196.1	195.1	195.6
		3	0+42B	118.0	196.0	195.0	195.5
		4	0+50B	118.0	195.7	194.7	195.2
		5	0+59B	118.0	192.2	191.2	191.7
		6	0+61.5B	118.0	189.8	188.9	189.4
		7	0+64B	118.0	187.3	186.4	186.9
		8	0+73B	118.0	184.3	183.3	183.8
		9	0+81B	118.0	184.3	183.1	183.7
		10	0+90B	118.0	184.2	183.1	183.7
		11	1+20B	118.0	187.5	186.1	186.8
		12	1+50B	116.8	189.0	188.0	188.5

Valve Opening, ft	Discharge, cfs	Piezometer			Pressure		
		Number	Station	Elevation	Minimum	Maximum	Observed Average
9.0	4770	1	0+20B	118.0	187.7	187.2	187.5
		2	0+38B	118.0	187.3	186.9	187.1
		3	0+42B	118.0	187.2	186.8	187.0
		4	0+50B	118.0	186.7	186.2	186.5
		5	0+59B	118.0	184.3	184.9	184.6
		6	0+61.5B	118.0	183.1	182.8	183.0
		7	0+64B	118.0	181.7	181.3	181.5
		8	0+73B	118.0	178.1	177.9	178.0
		9	0+81B	118.0	177.8	177.5	177.7
		10	0+90B	118.0	178.7	178.1	178.4
		11	1+20B	118.0	182.2	181.7	182.0
		12	1+50B	116.8	184.0	183.6	183.8
12.5	7090	1	0+20B	118.0	173.2	171.4	172.3
		2	0+38B	118.0	172.6	170.7	171.7
		3	0+42B	118.0	172.5	170.6	171.6
		4	0+50B	118.0	172.0	170.2	171.1
		5	0+59B	118.0	171.1	169.2	170.2
		6	0+61.5B	118.0	170.8	168.8	169.8
		7	0+64B	118.0	170.2	168.5	169.4
		8	0+73B	118.0	169.7	167.7	168.7
		9	0+81B	118.0	170.1	168.2	169.2
		10	0+90B	118.0	170.2	168.6	169.4
		11	1+20B	118.0	170.2	168.6	169.4
		12	1+50B	116.8	172.8	171.3	172.1
14.2	7440	1	0+20B	118.0	169.9	168.9	169.4
		2	0+38B	118.0	169.2	168.3	168.8
		3	0+42B	118.0	169.1	168.2	168.7
		4	0+50B	118.0	169.1	168.1	168.6
		5	0+59B	118.0	169.0	168.0	168.5
		6	0+61.5B	118.0	168.5	167.9	168.2
		7	0+64B	118.0	168.9	167.9	168.4
		8	0+73B	118.0	168.6	167.6	168.1
		9	0+81B	118.0	168.5	167.5	168.0
		10	0+90B	118.0	168.2	167.3	167.8
		11	1+20B	118.0	167.9	166.9	167.4
		12	1+50B	116.8	170.5	169.8	170.2

Note: Energy elevation immediately upstream from the culvert valve was maintained at approximately el 200. Hydraulic load equals total hoist load less load due to dry weight of the valve.

on the culvert soffit, 8.3 ft downstream of the valve well. This pressure cell location was 0.6 culvert heights downstream of the valve's culvert invert sill. The largest pressure drop across the valve was 11.5 ft, which was recorded at a 5.6 ft opening.

Each piezometer was located on the invert at the center of the culvert (Figure 13).

3.2 Type 2 valve

The stiffener plates across the web members, between the horizontal girders and the skin plate, were removed, and this configuration was designated the Type 2 valve. The section view of the 3D CAD models in Figure 22 illustrates the location of the stiffener plates that were removed. A photograph of the Type 2 valve is provided in Figure 23.

Hoist-load measurements made with the Type 2 valve are given in Table 4. Hoist loads for discharges corresponding to the 2 min valve schedule are shown in Figure 24. The removal of the stiffener plates caused a reduction in downpull of 3.3 kips at a 9.0 ft valve opening. Uplift was increased by 2.5 kips at a 12.5 ft opening. However, differences in maximum load variations with the Type 2 valve (Figure 25) did not differ significantly from the Type 1 valve. The hydraulic forces with the 2 min valve schedule are presented in Figure 26. The largest hydraulic force was 10.1 kips uplift and occurred when the valve was in the full-open position.

3.3 Type 3 valve

The Type 2 valve was modified in an attempt to reduce the hoist load variations. The top plate of the Type 2 valve was removed to form the Type 3 valve design. Vortices were believed to have been shedding from the top plate of the Type 2 valve when held at large valve openings. Further, this shedding action could generate dynamic loads, so removal of the top plate could reduce the load variations. The top plate is highlighted in red in the section view of Type 3 valve in Figure 22. The Type 3 valve, which resulted from the removal of the top plate and the stiffener plates, is shown in the photograph in Figure 23.

Figure 22. Oblique half-section view of Types 1 (original), 2, 3, 4, 5 (double-skin-plate), and 6 valves.

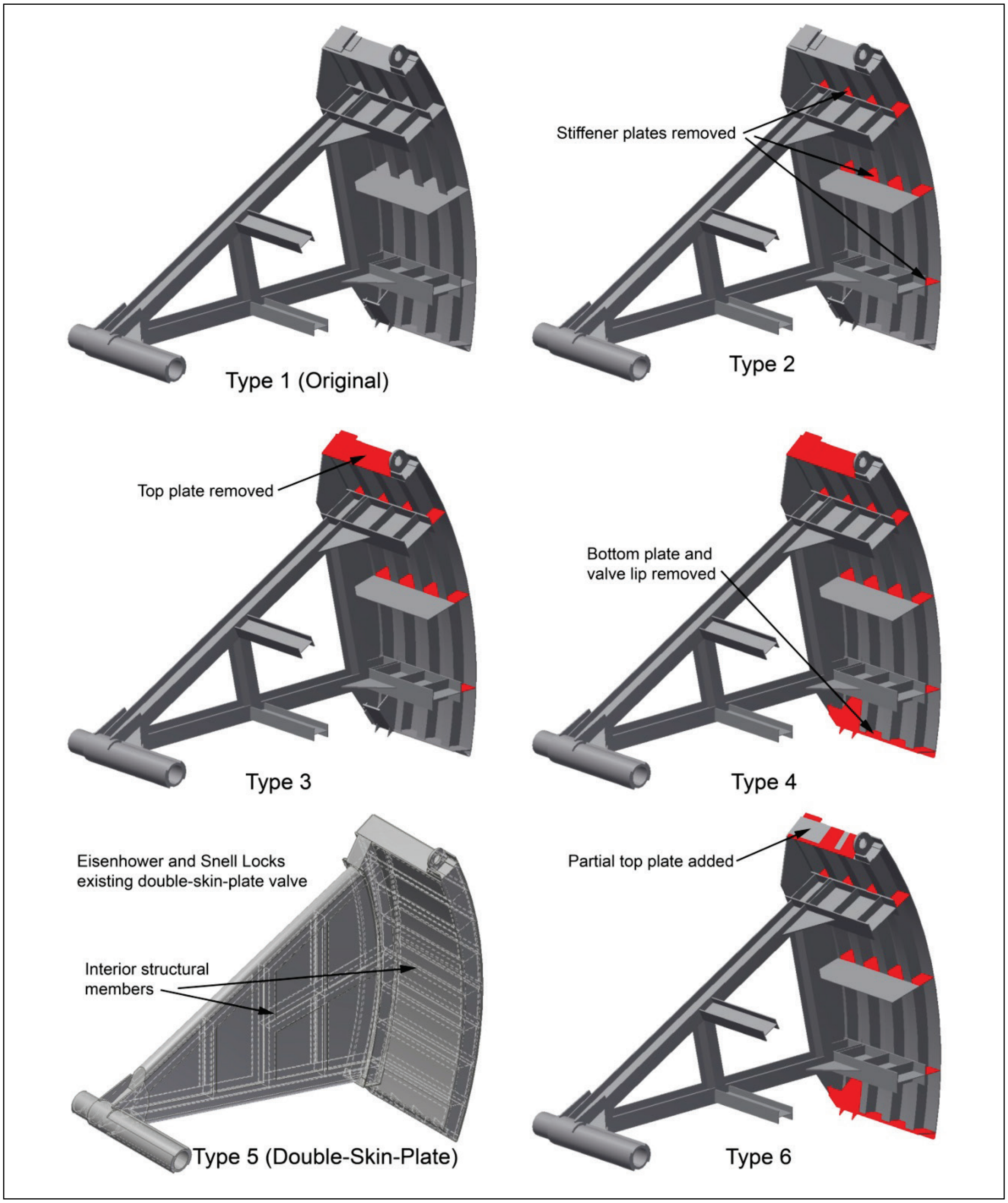


Figure 23. Types 1 (original), 2, 3, 4, 5 (double-skin-plate), and 6 valves.

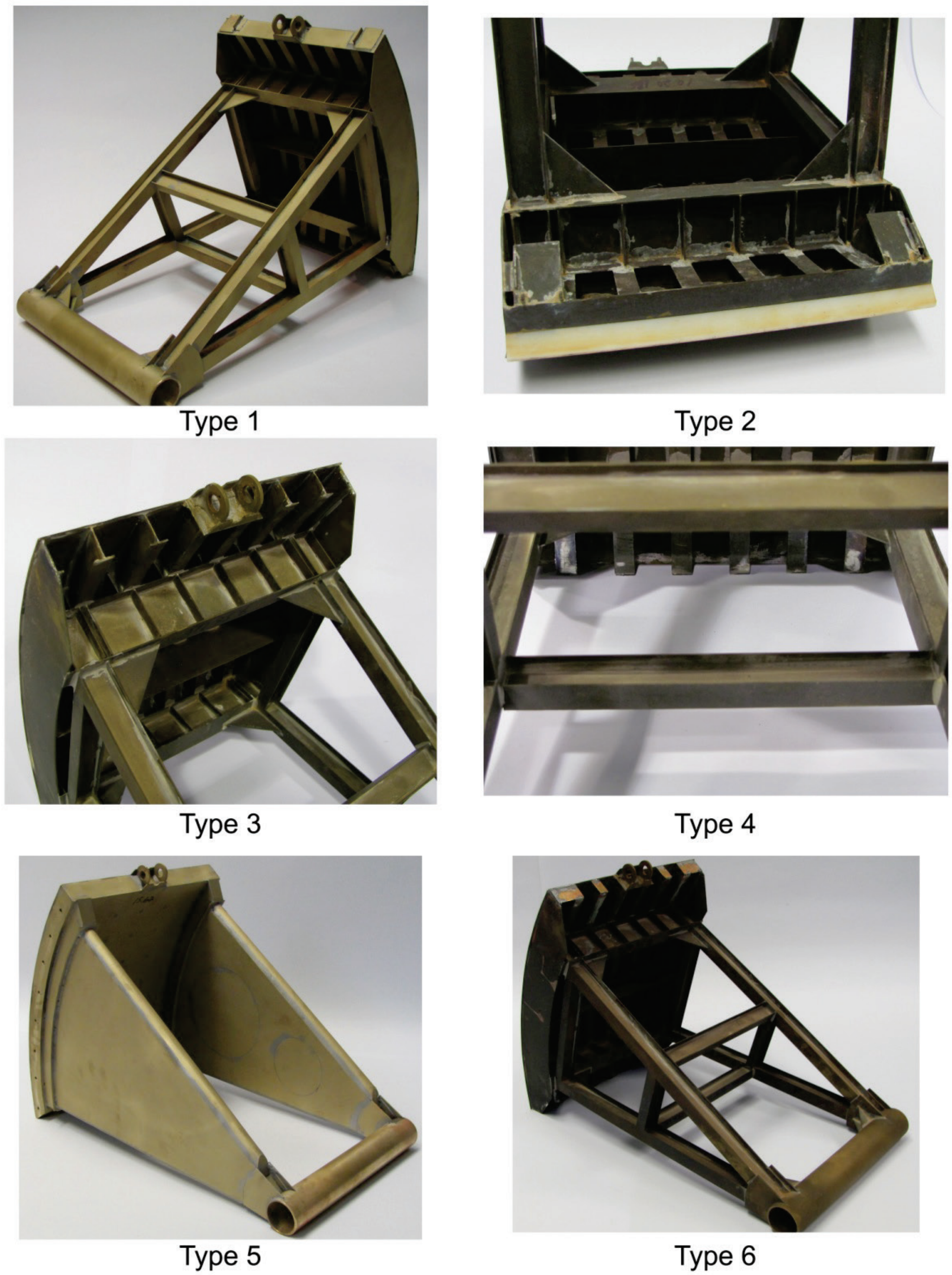


Table 4. Hoist loads, Type 2 valve.

Valve Opening, ft	Dry Valve Load, kips	Culvert Discharge, cfs	Total Hoist Load, kips		
			Minimum	Maximum	Observed Average
1.2	29.5	630			27.0
		730	26.2	28.0	27.2
		910	28.5	29.9	29.2
		1,090	31.8	33.2	32.5
2.6	30.7	1,240	27.8	29.1	28.4
		1,280	29.3	30.5	29.8
		1,550	30.6	32.3	31.4
		1,860	32.2	34.5	33.2
5.6	31.9	1,820	27.8	29.4	28.6
		2,270	29.6	31.8	30.6
		2,730	31.5	34.2	32.8
		2,740	35.1	38.9	37.0
9.0	34.0	2,570	28.6	30.9	29.7
		3,210	27.4	30.7	29.0
		3,850	28.9	32.7	30.6
		4,770	32.1	39.2	35.3
12.5	37.2	3,330	28.7	32.0	30.4
		4,160	28.7	32.9	30.8
		5,000	26.1	35.2	30.9
		6,640	24.3	36.0	30.2
		7,090	22.6	35.7	29.8
14.2	39.7	4,020	29.5	33.7	31.7
		5,030	25.6	35.8	31.2
		6,040	20.0	38.4	30.9
		6,490	24.7	34.9	30.3
		7,040	27.7	42.7	31.4
		7,440	21.5	36.2	29.6

Note: Energy elevation immediately upstream from the culvert valve was maintained at approximately el 200. Hydraulic load equals total hoist load less load due to dry weight of the valve.

Figure 24. Hoist load, Type 2 valve, 2 min valve schedule.

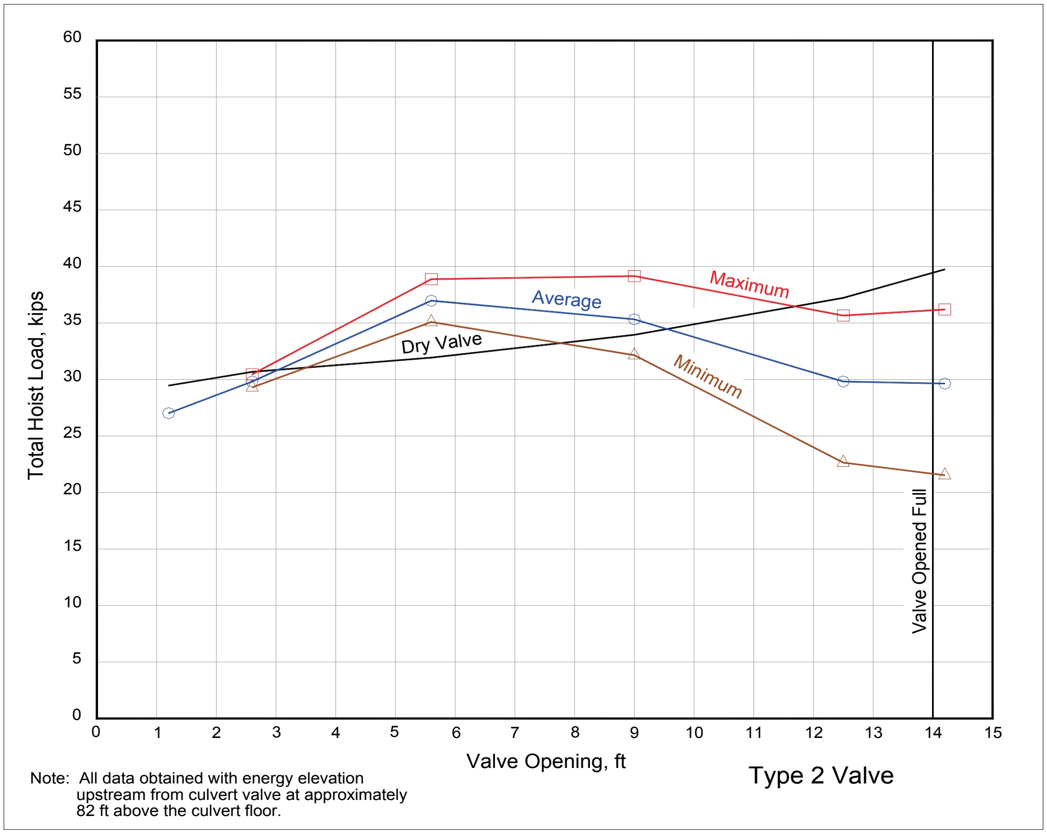


Figure 25. Maximum variation in total hoist load, Type 2 valve, 2 min valve schedule.

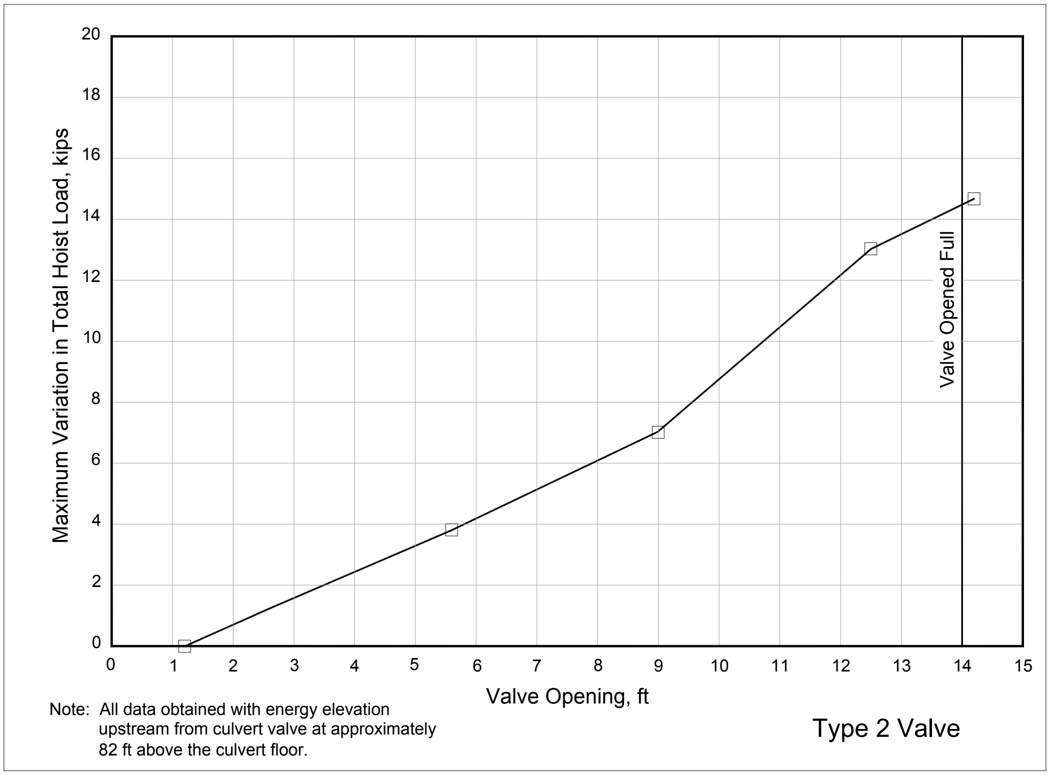
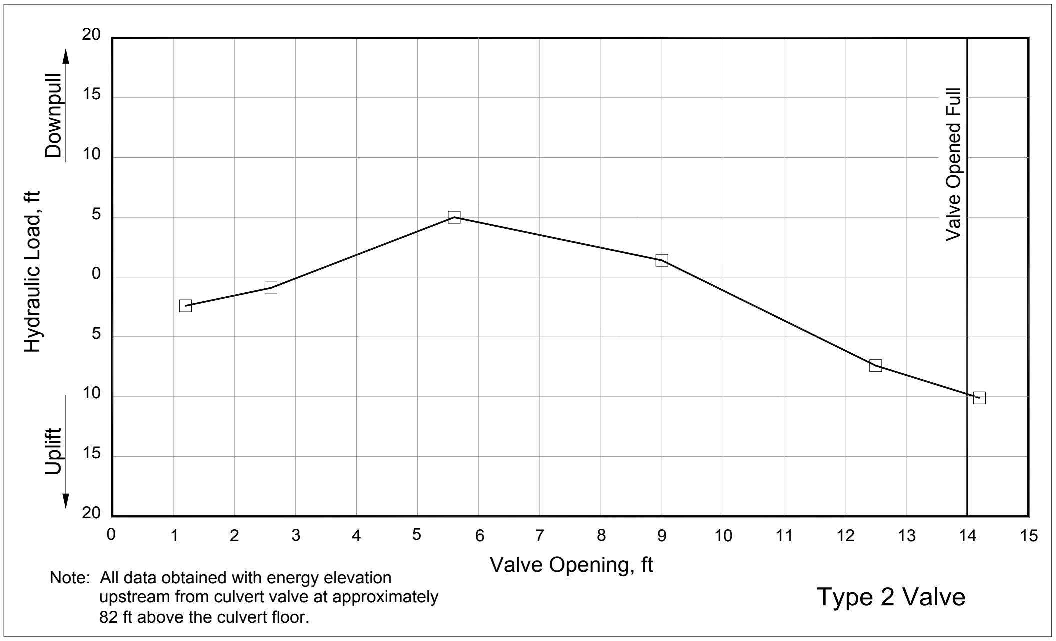


Figure 26. Hydraulic load, Type 2 valve, 2 min valve schedule.



Basic data for the Type 3 valve are listed in Table 5. Hoist loads measured with the 2 min valve schedule discharges are plotted in Figure 27. The maximum variation in hoist loads and the hydraulic loads with the Type 3 valve and a 2 min valve schedule are presented in Figure 28 and 29, respectively. The observed average loads did not vary much from those measured with the Type 2 valve. The ranges of maximum and minimum hoist loads were also similar to those with the Type 2 valve, except at a 5.6 ft opening where the loads varied 4 kips less than the Type 2 valve.

Removal of the top plate would require a redesign because this plate holds the strut connector, and it serves as a base for the valve stabilizer guides.

3.4 Type 4 valve

The flow path between the horizontal girders and the skin plate (between the ribs) was blocked by the stiffener plates, top plate, and bottom plate with valve lip as shown on the CAD model in Figure 22 and the photograph in Figure 23. The Type 4 valve was formed by removing the bottom plate and valve lip from the Type 3 valve. This modification provided flow area between the ribs as illustrated in the cutaway section in Figure 22. The bottom of the Type 4 valve is shown in the photograph in Figure 23. The removal of the stiffener plates and top plates from the Type 1 (original) valve had not only reduced the dry hoist load, but it had also increased the uplift of the hydraulic forces. The bottom plate was removed to try to further reduce the total hoist load.

Table 5. Hoist loads, Type 3 valve.

Valve Opening, ft	Dry Valve Load, kips	Culvert Discharge, cfs	Total Hoist Load, kips		
			Minimum	Maximum	Observed Average
1.2	28.4	630	N/A	N/A	N/A
		730	26.8	27.8	27.3
		910	28.0	29.4	28.8
		1,090	29.3	30.6	30.0
2.6	29.3	1,240	28.6	29.8	29.2
		1,280	31.1	32.4	31.7
		1,550	31.4	33.0	32.1
		1,860	31.7	34.0	32.8
5.6	30.8	1,820	28.1	29.7	28.8
		2,270	29.7	31.6	30.7
		2,730	31.5	34.3	32.9
		2,740	30.8	35.3	32.8
9.0	32.7	2,570	27.2	28.9	28.0
		3,210	28.3	30.9	29.6
		3,850	29.7	33.1	31.4
		4,770	30.4	37.0	33.6
12.5	36.0	3,330	28.2	31.3	29.8
		4,160	28.0	32.3	30.2
		5,000	25.3	33.9	29.7
		6,640	25.3	37.7	31.9
		7,090	24.9	38.8	32.0
14.2	38.0	4,020	29.5	33.0	31.3
		5,030	24.9	35.9	30.8
		6,040	22.0	37.2	30.7
		6,490	25.5	35.9	31.6
		7,040	27.4	34.1	31.0
		7,440	22.6	37.0	31.2

Note: Energy elevation immediately upstream from the culvert valve was maintained at approximately el 200. Hydraulic load equals total hoist load less load due to dry weight of the valve.

Figure 27. Hoist load, Type 3 valve, 2 min valve schedule.

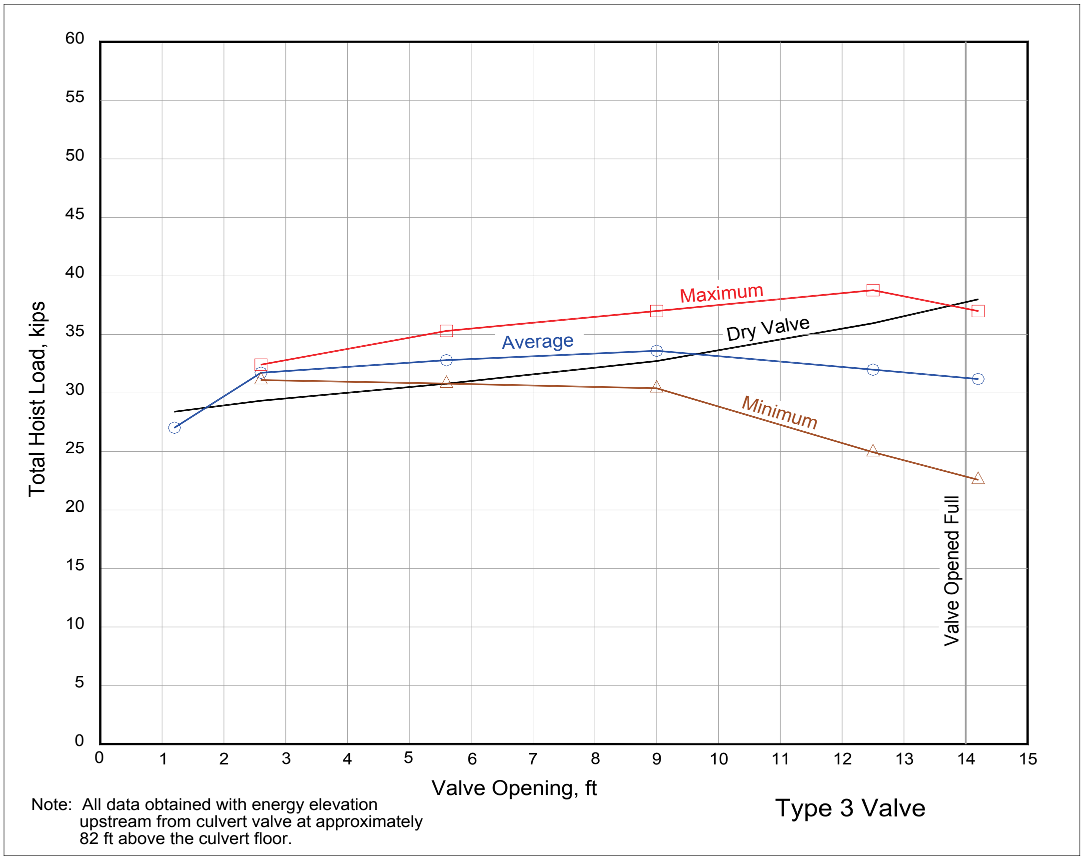


Figure 28. Maximum variation in total hoist load, Type 3 valve, 2 min valve schedule.

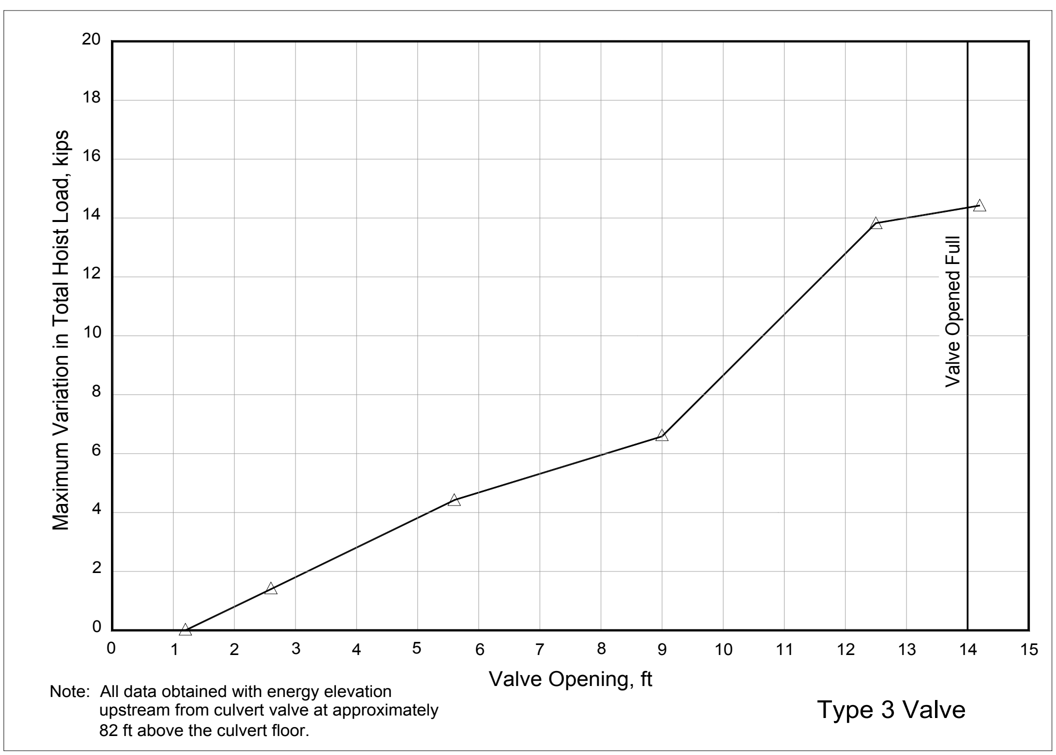
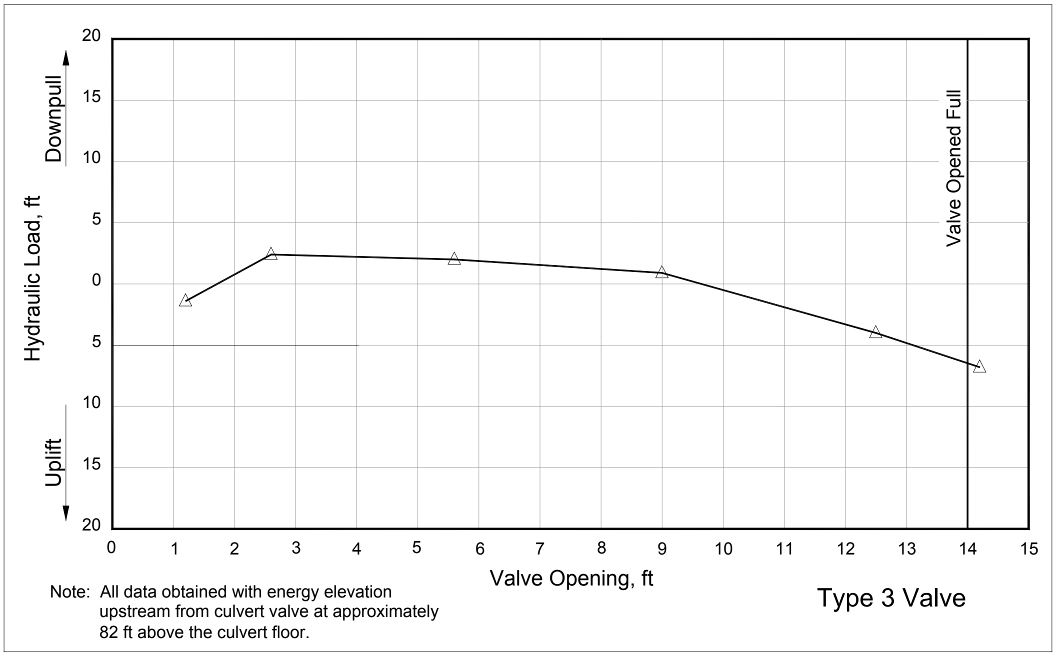


Figure 29. Hydraulic load, Type 3 valve, 2 min valve schedule.



Basic data for the Type 4 valve are listed in Table 6, and loads resulting from the 2 min valve schedule discharges are plotted in Figure 30. Elimination of the bottom plate and valve lip reduced the peak average total hoist loads throughout the operating cycle. The total hoist loads were less than the load on the hoist mechanism produced by the dry valve; thus, uplift due to hydraulic forces was indicated. The 2 min valve schedule discharges tended to lift the valve (Figure 30). Maximum load variations for discharges obtained with the 2 min valve schedule (Figure 31) were not significantly different than those obtained with the first three valve designs. Hydraulic loads on the valve, total hoist load minus dry valve (Figure 32), were 11.5 kips at 1.2 ft opening and 9.1 kips at 12.5 ft opening. The forces required to operate the Type 4 valve are less than those required for the first three designs tested. The peak average hoist load was about 28 kips as compared to 39 kips recorded with the Type 1 (original) valve.

Removal of the bottom plate caused the removal of the bottom seal. The resulting valve had a bottom that did not reach the culvert invert when the valve was fully closed. Even though the Type 4 valve was not practical for installation, it did show that the largest reduction in hoist loads occurred when all flow obstructions (stiffener plates, top plate, and bottom plate with seal) were removed.

Table 6. Hoist loads, Type 4 valve.

Valve Opening, ft	Dry Valve Load, kips	Culvert Discharge, cfs	Total Hoist Load, kips		
			Minimum	Maximum	Observed Average
1.2	27.3	630	N/A	N/A	N/A
		730	19.0	20.5	19.7
		910	21.8	23.0	22.4
		1,090	29.2	30.6	30.0
2.6	27.8	1,240	20.3	21.1	20.7
		1,280	22.5	23.5	22.9
		1,550	21.4	23.0	22.2
		1,860	23.0	24.2	23.6
5.6	29.2	1,820	21.7	22.8	22.2
		2,270	21.6	23.2	22.4
		2,730	21.6	23.8	22.6
		2,740	23.5	26.1	24.8
9.0	30.8	2,570	21.8	23.5	22.7
		3,210	21.2	23.9	22.6
		3,850	21.2	24.0	22.7
		4,770	19.8	26.1	23.4
12.5	33.4	3,330	23.0	27.2	25.8
		4,160	22.7	26.5	25.0
		5,000	19.1	26.2	23.8
		6,640	25.4	35.8	31.6
		7,090	16.3	29.4	24.3
14.2	35.4	4,020	24.6	28.4	26.7
		5,030	20.2	28.5	25.6
		6,040	16.2	30.2	25.6
		6,490	25.4	35.9	31.6
		7,040	21.4	27.5	25.0
		7,440	19.1	31.8	27.5

Note: Energy elevation immediately upstream from the culvert valve was maintained at approximately el 200. Hydraulic load equals total hoist load less load due to dry weight of the valve.

Figure 30. Hoist load, Type 4 valve, 2 min valve schedule.

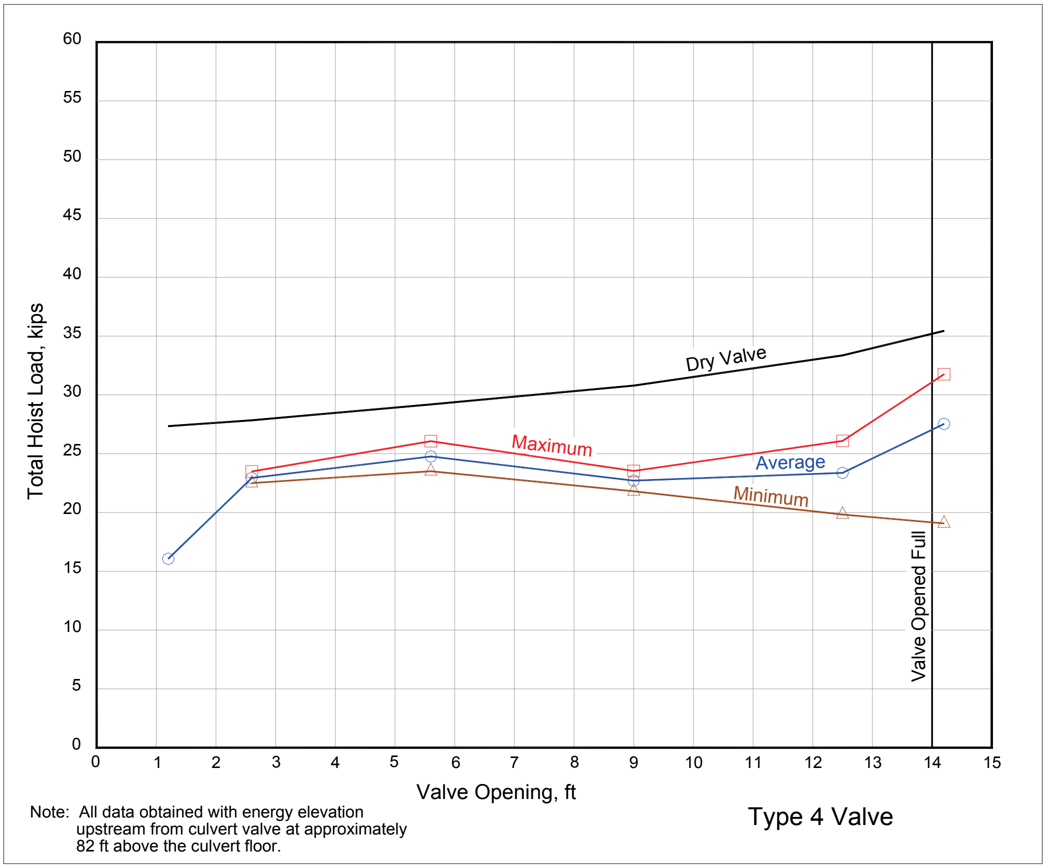


Figure 31. Maximum variation in total hoist load, Type 4 valve, 2 min valve schedule.

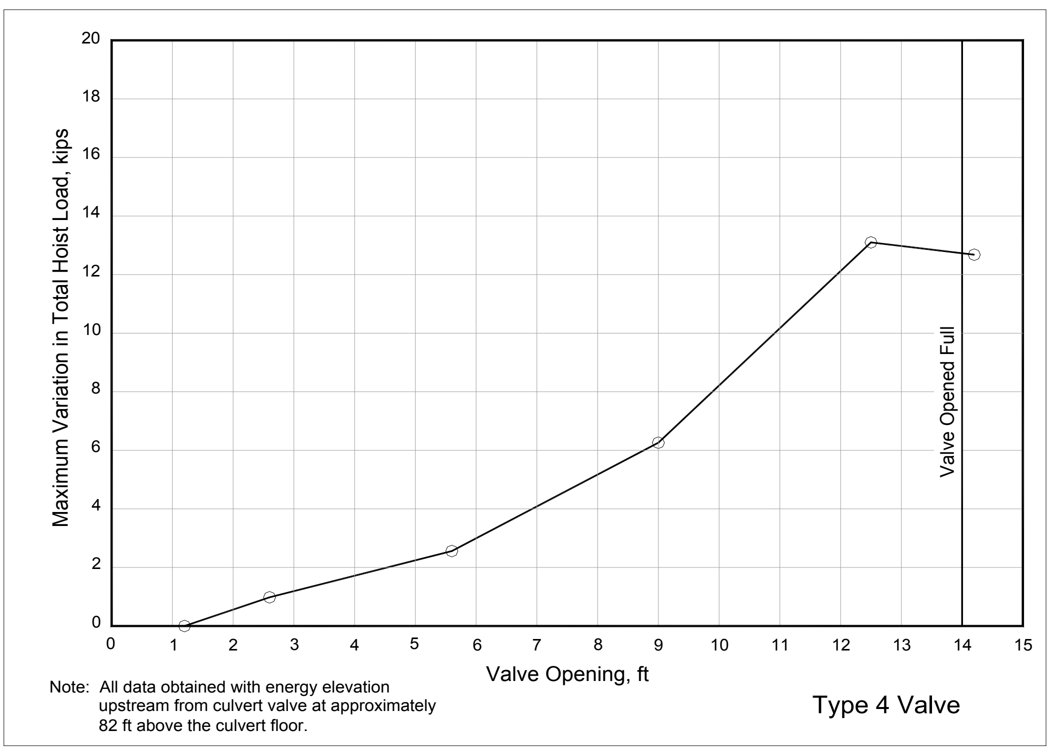
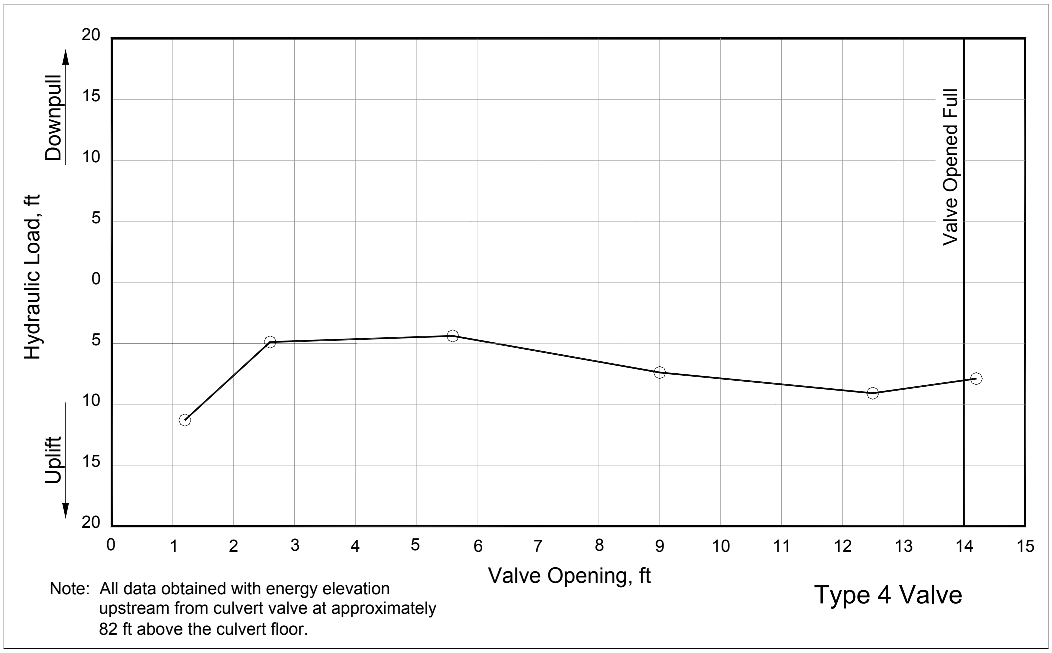


Figure 32. Hydraulic load, Type 4 valve, 2 min valve schedule.



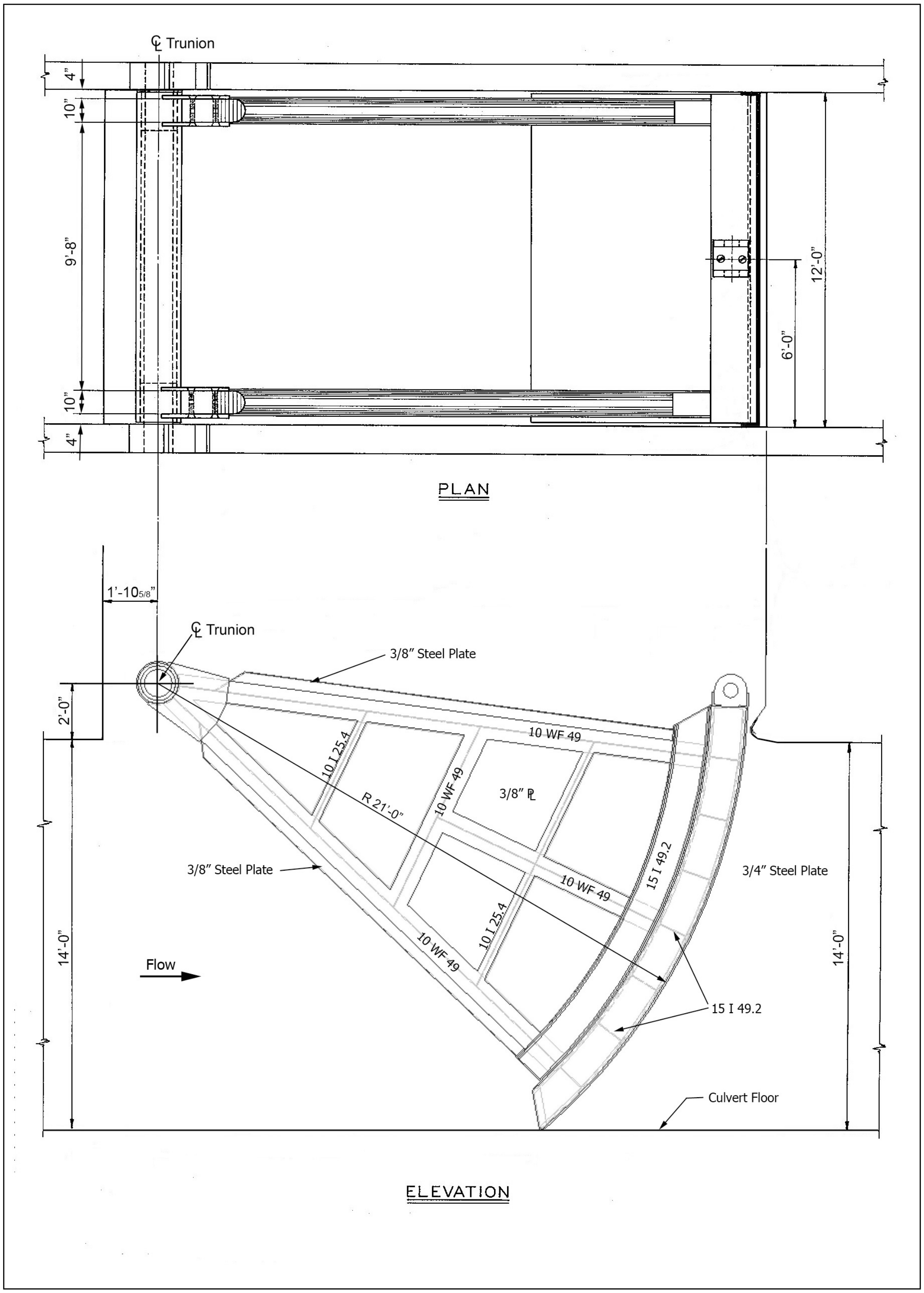
3.5 Type 5 (double-skin-plate) valve

At this point in the testing program, the double-skin-plate valve design, which has been successfully used on the locks for the last 50 years, was modeled so that comparison could be made with the vertical-frame valve designs. The double-skin-plate valve has its structural members wrapped in plate steel, which was thought to provide a more streamlined body (Headquarters, U.S. Army Corps of Engineers 1975). A model of the double-skin-plate valve was designated the Type 5 valve. The Type 5 model valve was constructed as closely to the prototype valve as possible so that the center-of-gravity would be properly located. Therefore, the internal structural members, which are not visible once the valve is complete, were included. The framing members of the Type 5 valve are shown in the half-section view in Figure 22. A photograph of the finished model valve is provided in Figure 23. Details of the steel framing and plate covering are given in Figure 33.

The valve's radius of 21 ft from the trunnion center to the downstream face of the valve's skin was identical to the vertical-frame valve. The valve's arms were made of 10WF49 steel members. The valve face was made of seven 15I49.2 steel ribs placed horizontally and supported by vertical 15I42.9 members, which were attached to the ends of the arms. The entire valve frame was covered with steel plating. The valve face consisted of three-quarter in. thick skin plate, and the arms were covered with three-

eighths in. steel plate. The three-eighths in. plating was rounded to make nine and one-half in. diameter semicircular noses and tails on the top and bottom of the valve arms.

Figure 33. Plan and elevation of the Type 5 (double-skin-plate) valve.



Hoist loads with the Type 5 (double-skin-plate) valve and the 2 min valve schedule discharges are plotted in Figure 34 and tabulated in Table 7. Small holes were placed in the Type 5 valve's skin plate along the outside edges so that it filled with water when submerged. The Type 5 valve is significantly heavier than the vertical-frame valve designs previously described. The load data provided in Table 7 and Figure 34 show that the Type 5 dry valve hoist loads vary from 38 kips at 1.2 ft opening to 51 kips at the full-open position of 14.2 ft. The Type 1 (original) valve was the heaviest vertical-frame valve design tested, and its dry hoist load varied from 30 to 41 kips.

Maximum variation in hoist loads with the Type 5 valve and discharges associated with a 2 min valve opening are shown in Figure 35. The load variations were significantly less than those measured with the vertical-frame valves (Types 1–4). The hydraulic loads (Figure 36) were uplift for each valve opening with each of the discharges tested.

Figure 34. Hoist load, Type 5 (double-skin-plate) valve, 2 min schedule.

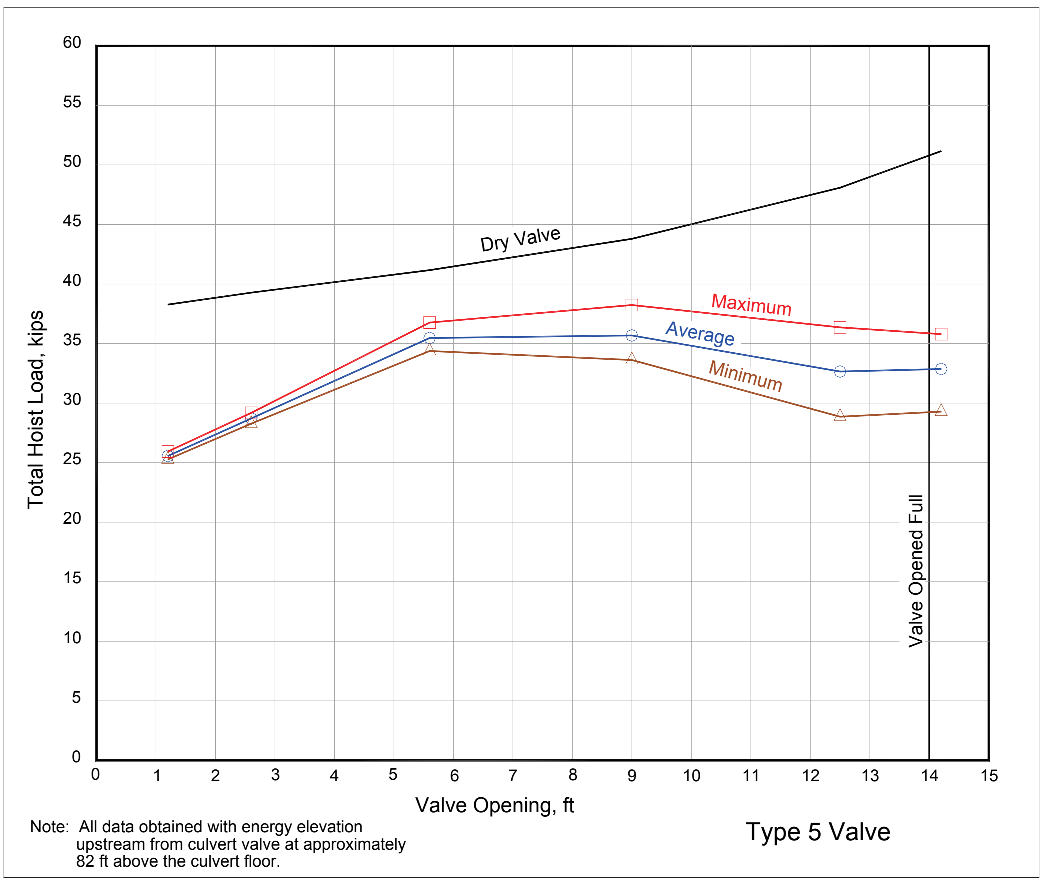


Table 7. Hoist loads, Type 5 (double-skin-plate) valve.

Valve Opening, ft	Dry Valve Load, kips	Culvert Discharge, cfs	Total Hoist Load, kips		
			Minimum	Maximum	Observed Average
1.2	38.3	630	25.3	25.9	25.6
		730	29.3	31.5	30.2
		910	29.6	31.3	30.4
		1,090	31.3	33.2	32.2
2.6	39.3	1,240	27.5	28.7	28.1
		1,280	28.3	29.2	28.7
		1,550	29.3	30.7	30.1
		1,860	32.0	33.7	32.9
5.6	41.2	1,820	27.6	28.4	28.0
		2,270	28.3	29.5	28.9
		2,730	30.0	31.3	30.7
		2,740	34.4	36.8	35.5
9.0	43.8	2,570	27.1	28.4	27.7
		3,210	27.9	29.5	28.7
		3,850	28.4	30.2	29.2
		4,770	33.6	38.2	35.7
12.5	48.1	3,330	28.0	30.0	29.0
		4,160	28.1	30.5	29.3
		5,000	27.5	31.7	29.6
		6,640	30.0	36.3	33.2
		7,090	28.9	36.4	32.7
14.2	51.2	4,020	27.1	29.9	28.3
		5,030	26.5	33.2	29.8
		6,040	23.4	37.6	29.8
		6,490	31.0	36.0	33.5
		7,040	27.2	31.2	29.4
		7,440	29.3	35.8	32.9

Note: Energy elevation immediately upstream from the culvert valve was maintained at approximately el 200. Hydraulic load equals total hoist load less load due to dry weight of the valve.

Figure 35. Maximum variation in total hoist load, Type 5 (double-skin-plate) valve, 2 min schedule.

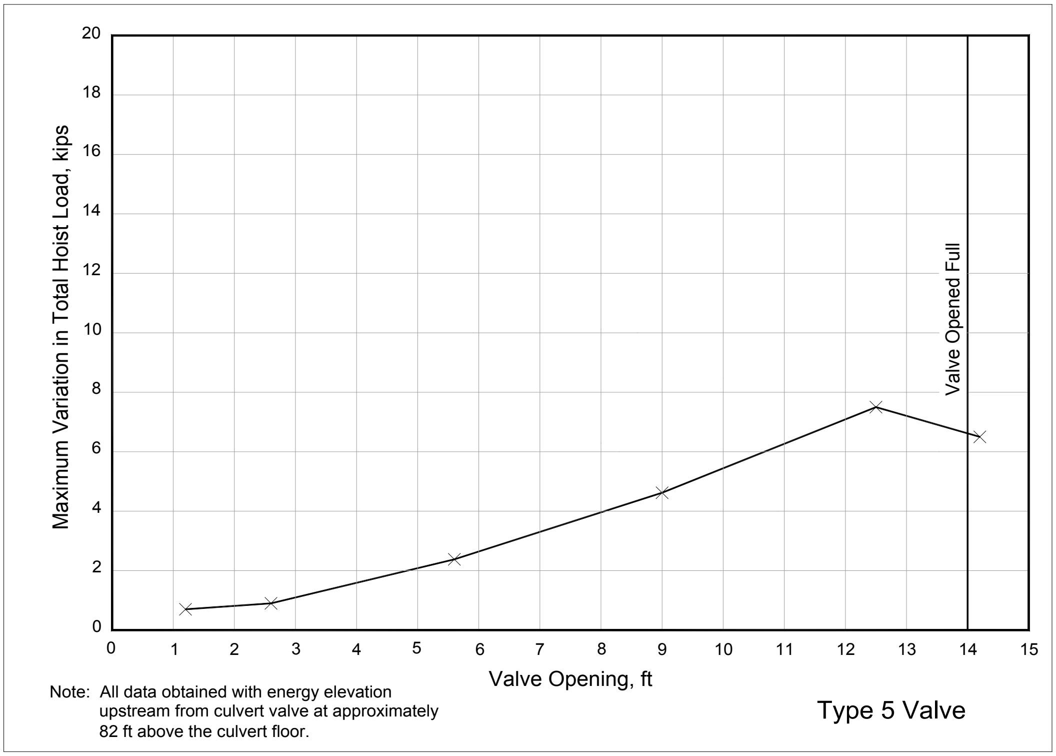
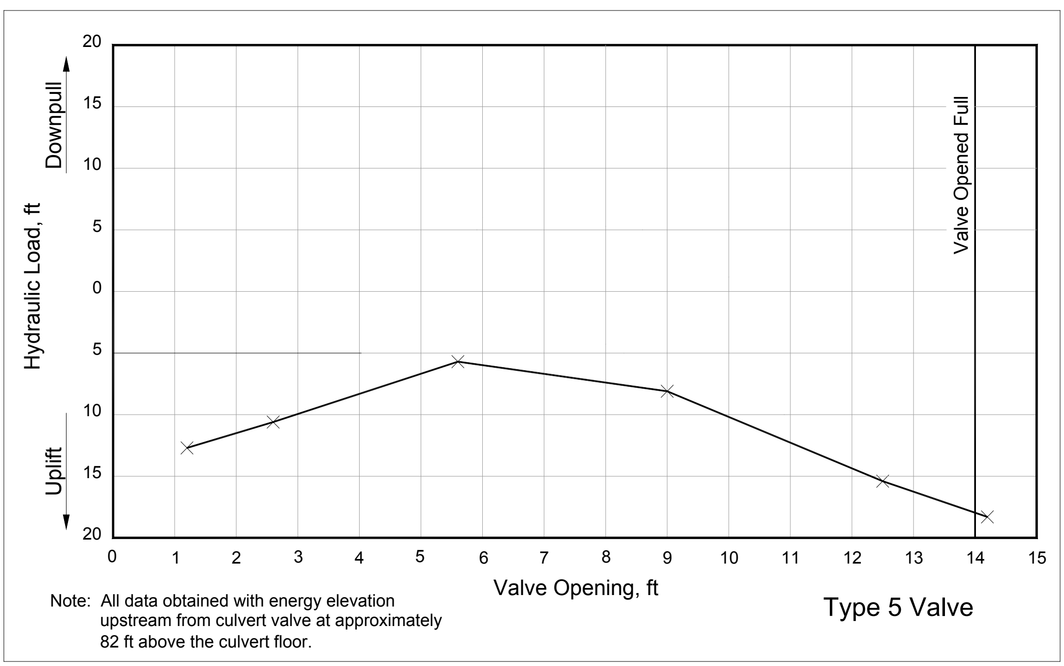


Figure 36. Hydraulic load, Type 5 (double-skin-plate) valve, 2 min schedule.



The energy loss as flow passes a double-skin-plate valve can be significantly different than losses with vertical-frame valve designs. Pressures with the Type 5 valve were recorded so that pressure distributions for the two

designs could be compared. Pressure data for the Type 5 valve is provided in Table 8. The largest pressure drop of 12.8 ft occurred at 5.6 ft opening. This pressure drop is 1.3 ft greater than the loss with the vertical-frame valve (Type 1 valve). The greatest pressure drop was at the 5.6 ft opening with both the vertical-frame and double-skin-plate valve designs.

3.6 Type 6 valve

The Type 6 valve consisted of the Type 4 valve with portions of the top plate added for structural and service reasons. The complete removal of the top plate, used with the Type 4 valve, was not practical because portions of this plate serve as a base for valve appurtenances. The ends of the top plate closest to the valve well walls serve as the base plate for the valve stabilizer guides. The center of the top plate holds the strut connector. The partial top plate of the Type 6 valve is shown in the CAD drawing in Figure 22 and the model photograph in Figure 23.

Hoist load data for the Type 6 valve are presented in Table 9. Loads on the valve for an opening time of 2 min are plotted in Figure 37. The largest average load was approximately 28.3 kips, and a maximum variation in total load was 14.0 kips when the valve is fully open (Figure 38). The hydraulic loads with the 2 min valve schedule are provided in Figure 39. Compared to the vertical-frame valve design that had no lateral plates (Type 4 valve), the partial top plate of the Type 6 valve resulted in approximately 1.5 kips additional hoist load at a 5.6 ft opening with a 2 min valve schedule.

3.7 Type 7 (recommended) valve

Experiments with the first five vertical-frame valve designs (Types 1–4 and Type 6) found that removing the top plate, bottom plate, and stiffener plates between the T-beams reduced the forces required to hoist the valve through flowing water. The Type 4 valve, with all lateral plates removed, produced the smallest hoist loads. However, a valve with no top or bottom plate, such as the Type 4 valve, was not practical for the Eisenhower and Snell Locks because portions of the top plate were required structurally, and the bottom plate held the bottom seal. Removal of the bottom seal plate resulted in the valve lip not reaching the culvert invert. With this in mind, SLSDC engineers designed a vertical-frame valve to meet the project requirements for stable lifting, while incorporating features that the model study had found reduced the hoist loads.

Table 8. Pressures in culvert, Type 5 (double-skin-plate) valve (Snell Lock), 2 min valve schedule.

Valve Opening, ft	Discharge, cfs	Piezometer			Pressure		
		Number	Station	Elevation	Minimum	Maximum	Observed Average
1.2	630	1	0+20B	118.0	199.8	199.7	199.8
		2	0+38B	118.0	199.8	199.7	199.8
		3	0+42B	118.0	199.8	199.7	199.8
		4	0+50B	118.0	199.8	199.7	199.8
		5	0+59B	118.0	194.7	194.3	194.5
		6	0+61.5B	118.0	194.3	194.0	194.2
		7	0+64B	118.0	194.0	193.8	193.9
		8	0+73B	118.0	193.9	193.8	193.9
		9	0+81B	118.0	194.0	193.8	193.9
		10	0+90B	118.0	193.9	193.8	193.9
		11	1+20B	118.0	194.5	194.2	194.4
		12	1+50B	116.8	194.6	194.4	194.5
2.6	1280	1	0+20B	118.0	199.1	199.0	199.1
		2	0+38B	118.0	199.1	199.0	199.1
		3	0+42B	118.0	199.1	199.0	199.1
		4	0+50B	118.0	198.9	198.8	198.9
		5	0+59B	118.0	194.1	194.0	194.1
		6	0+61.5B	118.0	190.1	190.0	190.1
		7	0+64B	118.0	188.8	188.7	188.8
		8	0+73B	118.0	188.4	188.1	188.3
		9	0+81B	118.0	188.5	188.2	188.4
		10	0+90B	118.0	188.5	188.3	188.4
		11	1+20B	118.0	189.8	189.9	189.9
		12	1+50B	116.8	190.7	190.5	190.6
5.6	2740	1	0+20B	118.0	196.1	195.7	195.9
		2	0+38B	118.0	196.1	195.6	195.9
		3	0+42B	118.0	196.0	195.5	195.8
		4	0+50B	118.0	195.6	195.0	195.3
		5	0+59B	118.0	192.2	191.8	192.0
		6	0+61.5B	118.0	189.7	189.9	189.8
		7	0+64B	118.0	186.5	186.0	186.3
		8	0+73B	118.0	182.9	182.1	182.5
		9	0+81B	118.0	182.9	182.2	182.6
		10	0+90B	118.0	183.1	182.4	182.8
		11	1+20B	118.0	185.4	184.9	185.2
		12	1+50B	116.8	187.4	187.0	187.2

Valve Opening, ft	Discharge, cfs	Piezometer			Pressure		
		Number	Station	Elevation	Minimum	Maximum	Observed Average
9.0	4770	1	0+20B	118.0	187.8	187.1	187.5
		2	0+38B	118.0	187.4	186.8	187.1
		3	0+42B	118.0	187.3	186.7	187.0
		4	0+50B	118.0	186.8	186.1	186.5
		5	0+59B	118.0	184.5	183.9	184.2
		6	0+61.5B	118.0	183.1	182.6	182.9
		7	0+64B	118.0	181.5	180.9	181.2
		8	0+73B	118.0	177.3	176.6	177.0
		9	0+81B	118.0	176.9	176.2	176.6
		10	0+90B	118.0	177.7	177.1	177.4
		11	1+20B	118.0	181.0	180.9	181.0
		12	1+50B	116.8	182.8	182.8	182.8
12.5	7090	1	0+20B	118.0	172.8	171.8	172.3
		2	0+38B	118.0	172.0	171.1	171.6
		3	0+42B	118.0	171.9	171.0	171.5
		4	0+50B	118.0	171.6	170.8	171.2
		5	0+59B	118.0	170.8	170.0	170.4
		6	0+61.5B	118.0	170.3	169.7	170.0
		7	0+64B	118.0	169.9	169.1	169.5
		8	0+73B	118.0	169.0	168.4	168.7
		9	0+81B	118.0	169.7	168.9	169.3
		10	0+90B	118.0	169.9	169.1	169.5
		11	1+20B	118.0	169.9	169.1	169.5
		12	1+50B	116.8	172.2	171.7	172.0
14.2	7440	1	0+20B	118.0	169.9	168.9	169.4
		2	0+38B	118.0	169.2	168.3	168.8
		3	0+42B	118.0	169.1	168.2	168.7
		4	0+50B	118.0	169.1	168.1	168.6
		5	0+59B	118.0	169.0	168.0	168.5
		6	0+61.5B	118.0	169.0	168.0	168.5
		7	0+64B	118.0	168.9	167.9	168.4
		8	0+73B	118.0	168.6	167.7	168.2
		9	0+81B	118.0	168.5	167.6	168.1
		10	0+90B	118.0	168.2	167.4	167.8
		11	1+20B	118.0	168.0	167.0	167.5
		12	1+50B	116.8	170.3	169.6	170.0

Table 9. Hoist loads, Type 6 valve.

Valve Opening, ft	Dry Valve Load, Kips	Culvert Discharge, cfs	Total Hoist Load, kips		
			Minimum	Maximum	Observed Average
1.2	28.1	630	N/A	N/A	N/A
		730	21.1	22.0	21.5
		910	21.3	22.3	21.8
		1,090	21.8	22.8	22.2
2.6	28.9	1,240	22.0	23.2	22.5
		1,280	23.8	24.7	24.2
		1,550	22.9	24.1	23.4
		1,860	23.8	25.1	24.4
5.6	30.1	1,820	24.5	25.9	25.2
		2,270	24.7	26.3	25.5
		2,730	24.6	26.8	25.7
		2,740	24.7	27.7	26.2
9.0	32.0	2,570	24.5	26.4	25.5
		3,210	24.0	26.7	25.5
		3,850	23.2	27.0	25.6
		4,770	21.8	28.1	25.2
12.5	34.9	3,330	25.7	28.8	27.4
		4,160	25.2	29.2	27.6
		5,000	22.6	29.4	26.6
		6,640	17.9	30.3	25.9
		7,090	16.8	30.8	25.3
14.2	37.0	4,020	27.3	31.0	29.7
		5,030	23.0	31.9	28.7
		6,040	20.4	32.4	28.4
		6,490	22.4	32.3	29.0
		7,040	25.6	31.4	29.2
		7,440	19.0	32.9	28.3

Note: Energy elevation immediately upstream from the culvert valve was maintained at approximately el 200. Hydraulic load equals total hoist load less load due to dry weight of the valve.

Figure 37. Hoist load, Type 6 valve, 2 min valve schedule.

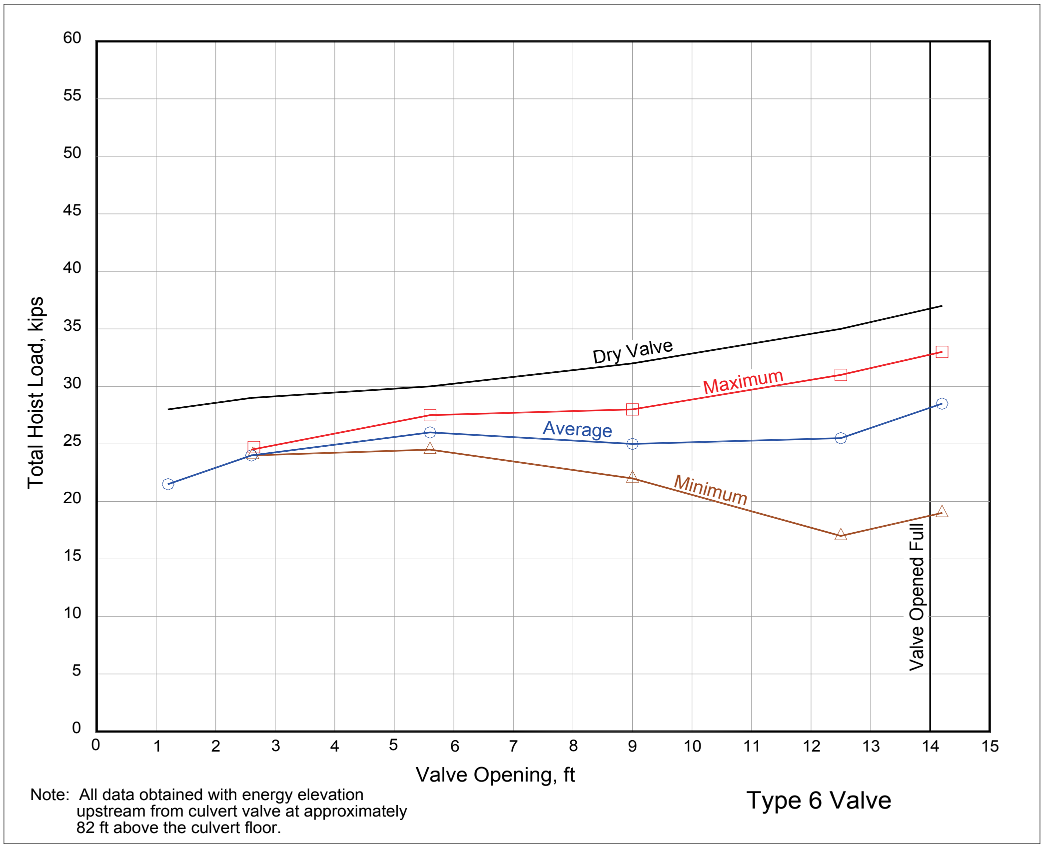


Figure 38. Maximum variation in total hoist load, Type 6 valve, 2 min valve schedule.

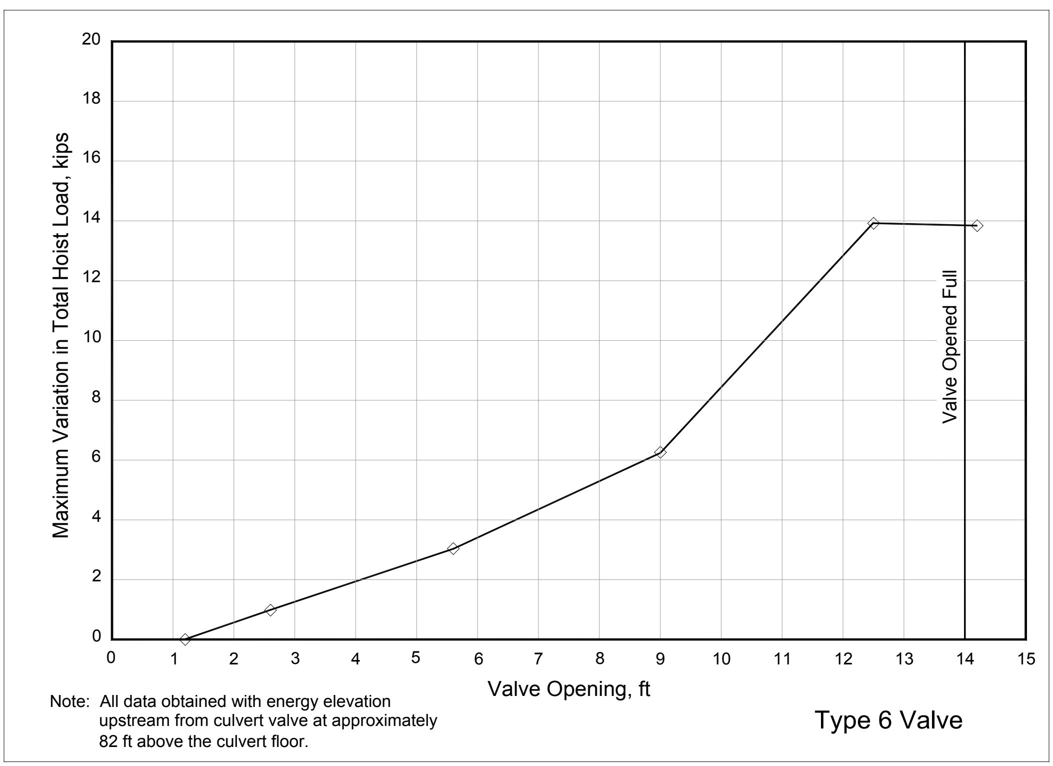
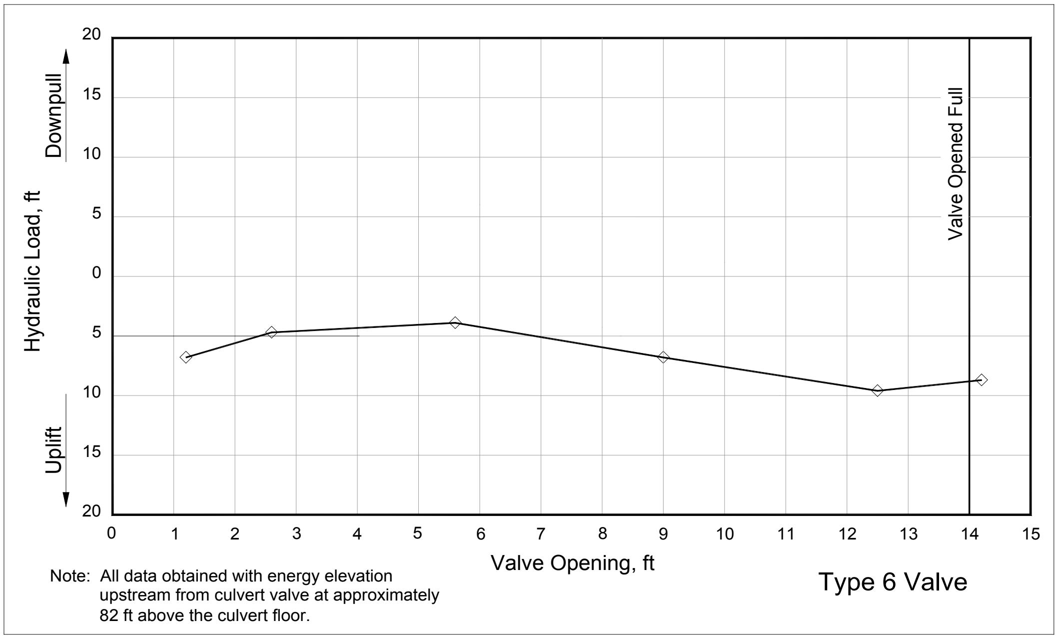


Figure 39. Hydraulic load, Type 6 valve, 2 min valve schedule.



The newly designed vertical-frame valve was designated the Type 7 valve, details of which are shown in Figure 40. The Type 7 valve did not have a bottom plate. The design included a sharp lip at the lower edge of the skin plate, which is in accordance with guidance provided in Engineer Manual 1110-2-1610, *Hydraulic Design of Lock Culvert Valves* (HQUSACE 1975). USACE guidance calls for vertical-frame reverse tainter valves to have a sharp-edged lip at the bottom of the ribs and skin plate. The Type 7 valve had a 21 ft radius, and the trunnion arms were W12 × 58 steel members, both similar to the previously tested vertical-frame valves. Absence of lateral plates on the Type 7 valve design provided open areas between the ribs for flow to pass along the upstream side of the skin plate. The ribs were slightly stiffer since they were made of WT12 × 42 wide-flange-tee steel members rather than the WT12 × 31 steel members used in the Type 1 (original) valve design. The WT12 × 42 T-beams also provided a little more flow area (0.18 ft more clearance) between the skin plate and horizontal girders as compared to the WT12 × 31 T-beams. A three-fourths in. thick skin plate was mounted on the downstream side of the ribs. Two horizontal W24 × 104 steel wide-flange girders were mounted horizontally to the trunnion arms just upstream of the web members. The partial top plate was a one-half in. thick steel plate that was placed laterally across approximately one-half of the top of the ribs. The center of the top plate provided a base for the strut connector, and each end of the top plate was for the stabilizer guides mounted adjacent to the walls. The partial top plate on the Type 7 design is shown in the model photograph in Figure 41.

Figure 40. Plan and elevation of the Type 7 (recommended) valve.

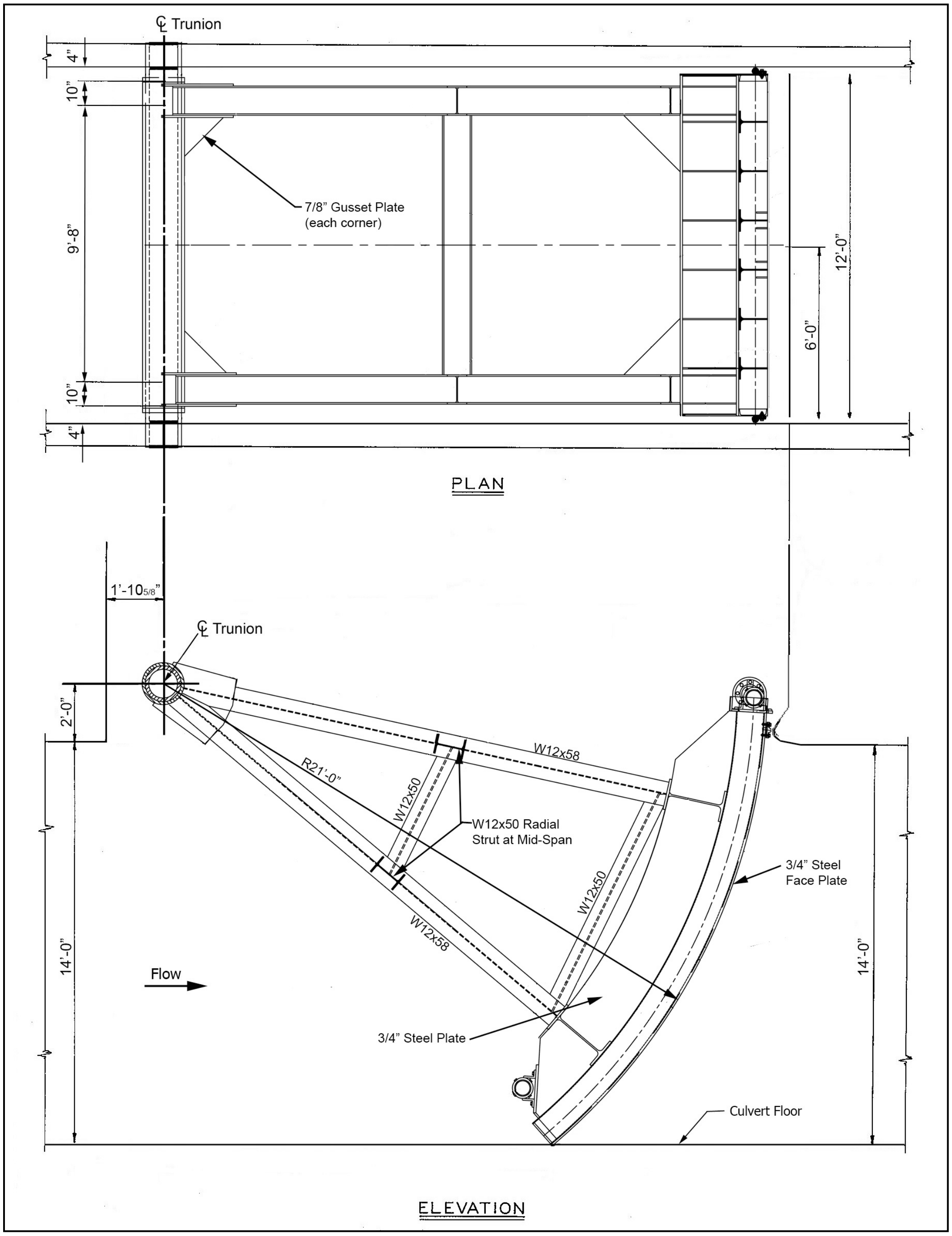
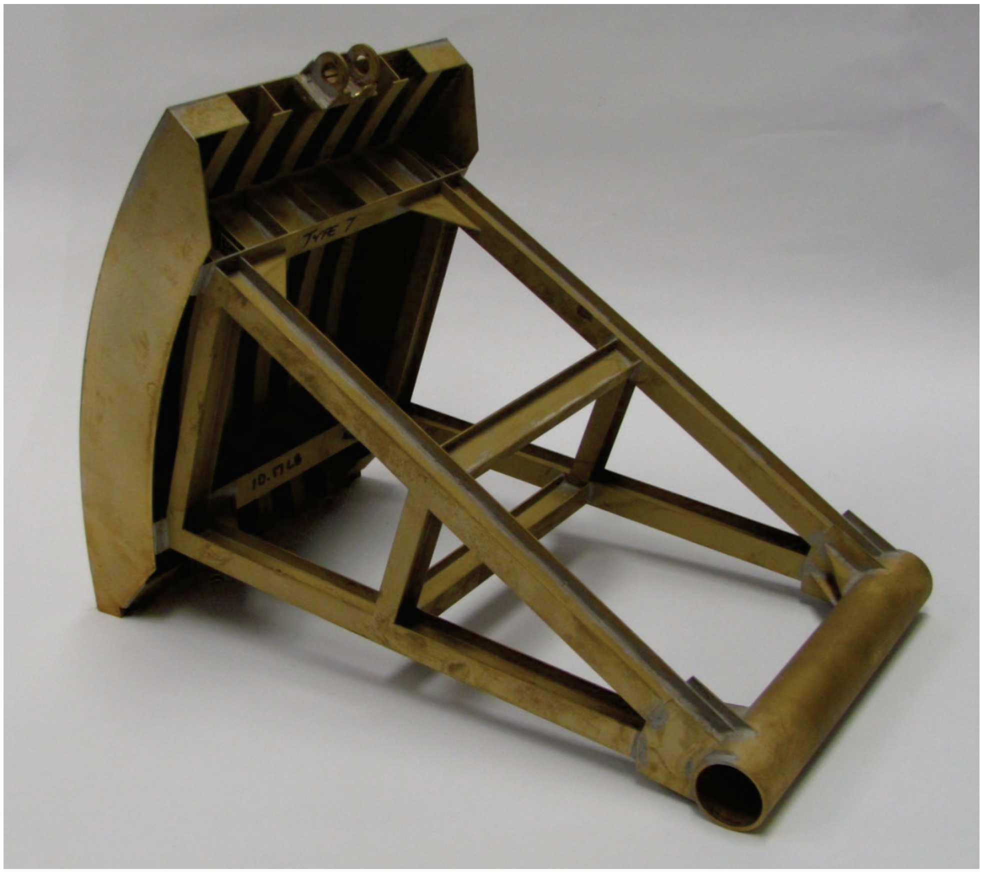


Figure 41. 1:15-scale model of Type 7 (recommended) valve.



Experiments were conducted with the Type 7 valve to measure the hoist loads and pressure distribution as flow passed the valve. Hoist loads for the Type 7 valve are listed on Table 10 for various open positions ranging from 1.2 ft to fully open. The hoist loads for the discharges corresponding to the 2 min valve schedule are plotted in Figure 42. The largest average load was approximately 30.9 kips, and a maximum variation in total load was 11.3 kips when the valve was in the full-open position (Figure 43). The largest average hoist loads were less than 26 kips over most of the range of valve openings tested. The average hoist load was 26.6 kips at a 12.5 ft valve opening and 2 min valve schedule. Figure 44 illustrates that the hydraulic loads with this condition were uplifts that varied approximately 14.4 kips, between 21.7 kips and 7.3 kips.

Table 10. Hoist loads, Type 7 valve.

Valve Opening, ft	Dry Valve Load, kips	Culvert Discharge, cfs	Total Hoist Load, kips		
			Minimum	Maximum	Observed Average
1.2	31.2	630	21.0	23.7	22.9
		730	20.5	22.0	21.3
		910	20.7	21.9	21.4
		1,090	21.0	22.0	21.5
2.6	32.0	1,240	23.1	24.1	23.6
		1,280	23.8	24.8	24.3
		1,550	22.9	24.0	23.5
		1,860	22.9	24.0	23.5
5.6	33.8	1,820	25.1	26.1	25.6
		2,270	25.1	26.5	25.9
		2,730	25.3	26.8	26.1
		2,740	22.5	26.2	24.7
9.0	36.0	2,570	24.8	27.2	26.3
		3,210	24.8	27.2	26.2
		3,850	24.4	27.4	26.1
		4,770	20.6	27.9	24.6
12.5	39.4	3,330	28.3	31.0	29.9
		4,160	27.8	31.2	29.9
		5,000	26.1	32.6	30.3
		6,640	23.6	34.8	30.5
		7,090	17.7	32.1	26.6
14.2	42.5	4,020	33.3	36.7	35.3
		5,030	30.0	35.8	33.7
		6,040	28.2	36.5	33.6
		6,490	27.1	36.7	33.4
		7,040	25.5	36.9	33.2
		7,440	23.5	34.8	30.9

Note: Energy elevation immediately upstream from the culvert valve was maintained at approximately el 200. Hydraulic load equals total hoist load less load due to dry weight of the valve.

Figure 42. Hoist load, Type 7 (recommended) valve, 2 min valve schedule.

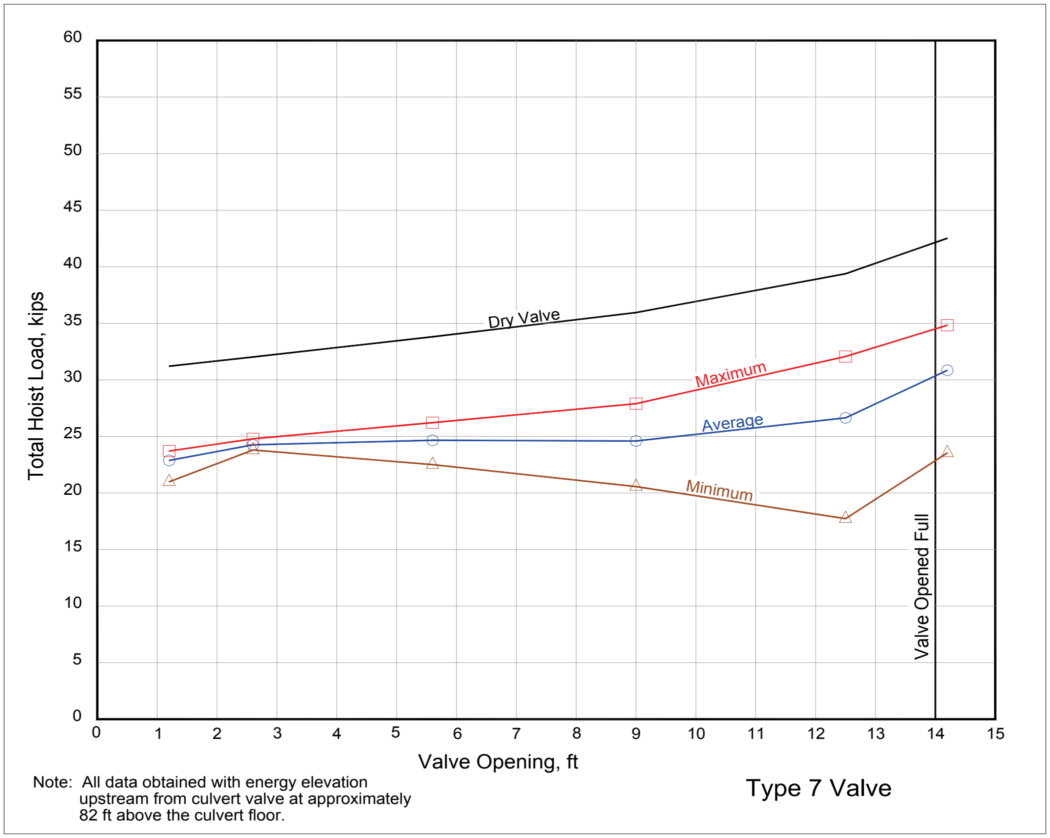


Figure 43. Maximum variation in total hoist load, Type 7 (recommended) valve, 2 min valve schedule.

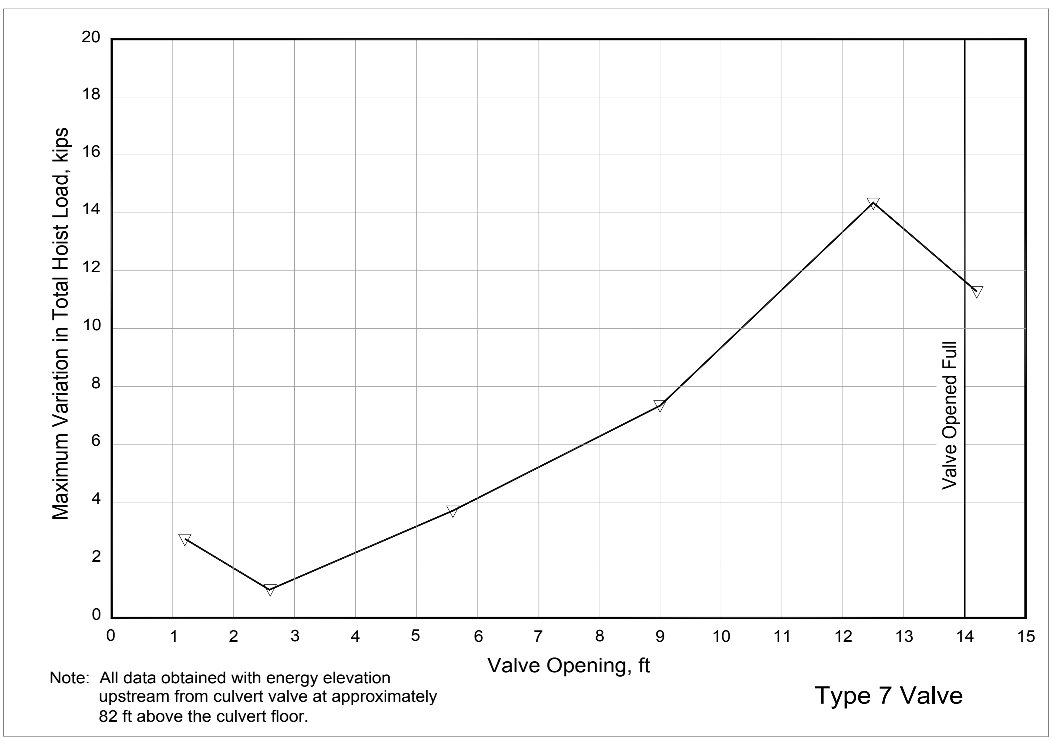
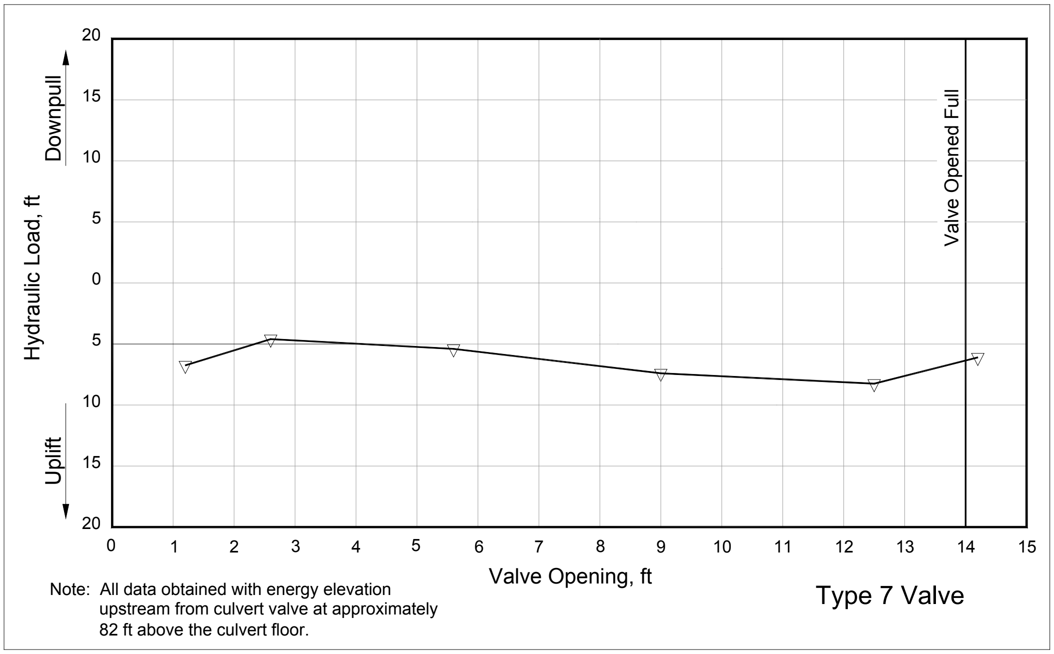


Figure 44. Hydraulic load, Type 7 (recommended) valve, 2 min valve schedule.



Pressures measured in the culvert with flow conditions associated with a 2 min valve schedule are presented in Table 11. Locations of the piezometers and the pressure cell are shown in Figure 13. The pressure drop across the valve was 20.1 ft when the valve was opened 5.6 ft.

3.8 Alternate filling valve schedules

Occasionally, the Eisenhower and Snell Locks are filled slowly by opening the valves to a position less than or equal to 50% open, where they are held until the lock is filled. Valve vibrations have sometimes been a problem during said conditions. Additional numerical model simulations were made to determine the flow conditions when the locks are filled slowly. Two lock-filling operations were simulated. Both simulations modeled the valves opening at the 2 min rate prior to stopping in a partially opened position, where they remained until the lock filled.

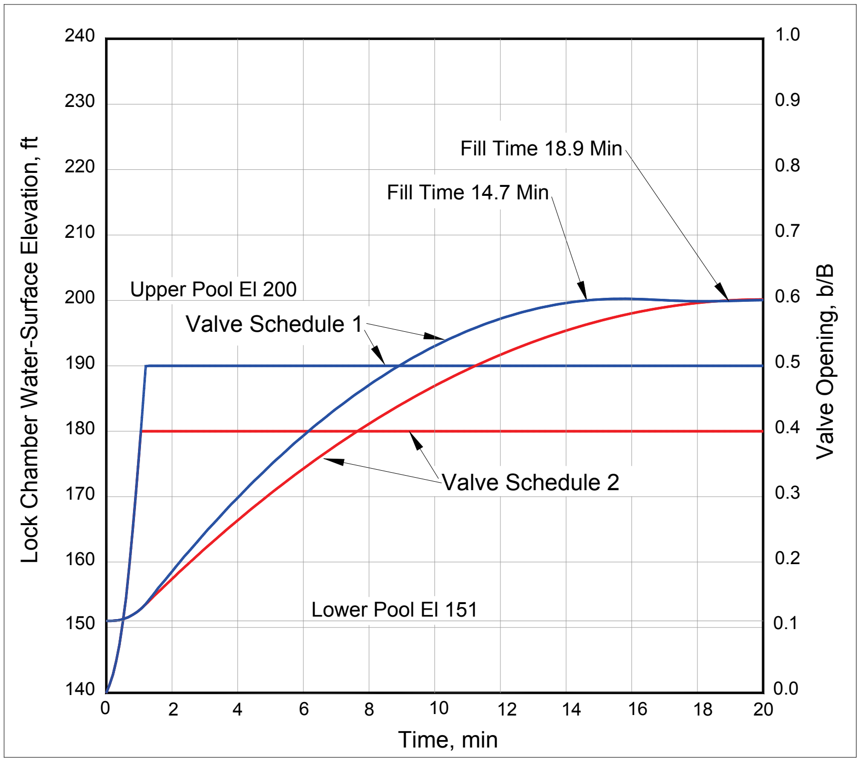
The first slow-filling operation modeled the valves stopping at the 50% open position (Valve Schedule 1, Figure 45), and the second slow-filling operation had the valves stop at the 40% open position (Valve Schedule 2, Figure 45). At the 2 min valve opening rate, the reverse tainter valve reaches the 40% position in 63 sec and the 50% position in 78 sec.

Table 11. Pressures in culvert, Type 7 valve (Snell Lock), 2 min valve schedule.

Valve Opening, ft	Discharge, cfs	Piezometer			Pressure		
		Number	Station	Elevation	Minimum	Maximum	Observed Average
1.2	630	1	0+20B	118.0	199.7	199.9	199.8
		2	0+38B	118.0	199.7	199.9	199.8
		3	0+42B	118.0	199.7	199.8	199.8
		4	0+50B	118.0	199.7	199.8	199.8
		5	0+59B	118.0	173.9	174.0	174.0
		6	0+61.5B	118.0	171.8	171.9	171.9
		7	0+64B	118.0	170.3	170.5	170.4
		8	0+73B	118.0	169.8	169.9	169.9
		9	0+81B	118.0	169.8	169.8	169.8
		10	0+90B	118.0	169.4	169.7	169.6
		11	1+20B	118.0	171.3	171.5	171.4
		12	1+50B	116.8	172.3	172.4	172.4
2.6	1280	1	0+20B	118.0	199.0	199.1	199.1
		2	0+38B	118.0	199.0	199.1	199.1
		3	0+42B	118.0	199.0	199.1	199.1
		4	0+50B	118.0	198.9	199.0	199.0
		5	0+59B	118.0	191.3	191.5	191.4
		6	0+61.5B	118.0	183.3	183.3	183.3
		7	0+64B	118.0	180.9	181.0	181.0
		8	0+73B	118.0	180.2	180.3	180.3
		9	0+81B	118.0	180.3	180.5	180.4
		10	0+90B	118.0	180.2	180.3	180.3
		11	1+20B	118.0	182.1	182.2	182.2
		12	1+50B	116.8	183.4	183.5	183.5
5.6	2740	1	0+20B	118.0	195.7	196.2	196.0
		2	0+38B	118.0	195.4	196.0	195.7
		3	0+42B	118.0	195.3	196.0	195.7
		4	0+50B	118.0	194.9	195.6	195.1
		5	0+59B	118.0	190.6	195.2	192.9
		6	0+61.5B	118.0	186.1	186.9	186.5
		7	0+64B	118.0	180.9	181.7	181.3
		8	0+73B	118.0	175.1	176.1	175.6
		9	0+81B	118.0	175.2	176.3	175.8
		10	0+90B	118.0	175.7	176.9	176.3
		11	1+20B	118.0	179.1	180.0	179.6
		12	1+50B	116.8	181.8	182.2	182.0

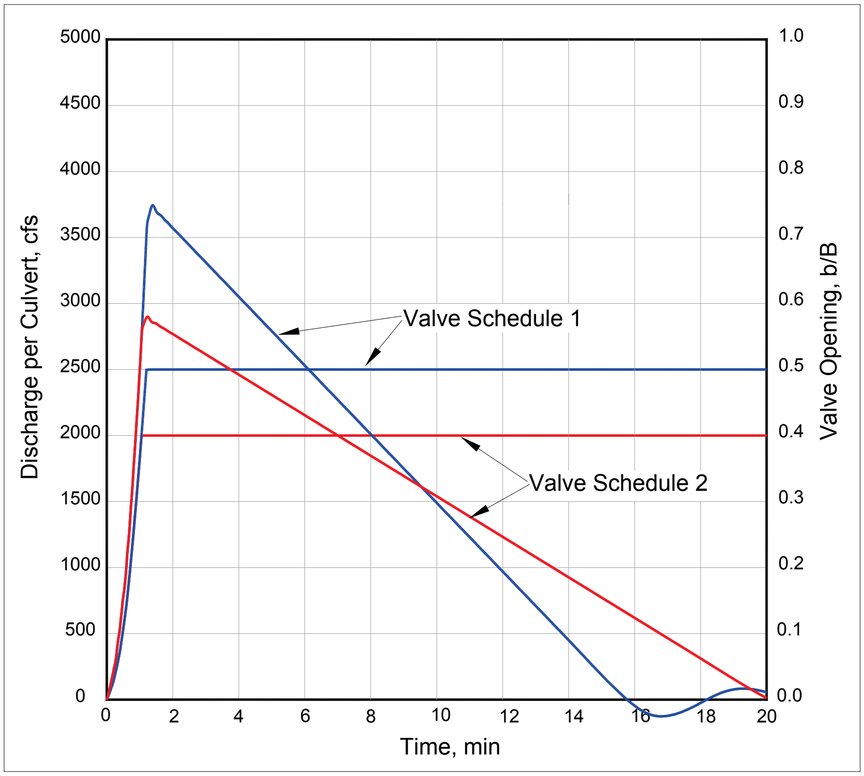
Valve Opening, ft	Discharge, cfs	Piezometer			Pressure		
		Number	Station	Elevation	Minimum	Maximum	Observed Average
9.0	4770	1	0+20B	118.0	187.2	187.7	187.5
		2	0+38B	118.0	186.9	187.3	186.1
		3	0+42B	118.0	186.8	187.2	187.0
		4	0+50B	118.0	186.2	186.8	186.5
		5	0+59B	118.0	187.7	184.1	183.9
		6	0+61.5B	118.0	182.0	182.5	182.3
		7	0+64B	118.0	179.9	180.2	180.1
		8	0+73B	118.0	174.6	175.0	174.8
		9	0+81B	118.0	174.2	174.7	174.5
		10	0+90B	118.0	175.3	175.4	175.4
		11	1+20B	118.0	179.2	179.3	179.3
		12	1+50B	116.8	181.4	181.5	181.5
12.5	7090	1	0+20B	118.0	171.7	172.6	172.2
		2	0+38B	118.0	171.0	172.0	171.5
		3	0+42B	118.0	170.9	171.8	171.4
		4	0+50B	118.0	170.6	171.5	171.1
		5	0+59B	118.0	169.6	170.3	170.0
		6	0+61.5B	118.0	169.0	169.9	169.5
		7	0+64B	118.0	168.4	169.3	168.8
		8	0+73B	118.0	167.1	168.1	167.6
		9	0+81B	118.0	167.8	167.8	167.8
		10	0+90B	118.0	168.2	169.1	168.7
		11	1+20B	118.0	168.7	169.4	169.1
		12	1+50B	116.8	170.1	171.9	171.0
14.2	7440	1	0+20B	118.0	168.8	170.1	169.5
		2	0+38B	118.0	168.0	169.4	168.7
		3	0+42B	118.0	168.0	169.3	168.7
		4	0+50B	118.0	167.9	169.3	168.6
		5	0+59B	118.0	167.8	169.0	168.4
		6	0+61.5B	118.0	167.8	169.0	168.4
		7	0+64B	118.0	167.7	168.9	168.3
		8	0+73B	118.0	167.3	168.7	168.0
		9	0+81B	118.0	167.2	168.6	167.9
		10	0+90B	118.0	167.0	168.2	167.6
		11	1+20B	118.0	166.8	167.8	167.3
		12	1+50B	116.8	169.6	170.6	170.1

Figure 45. Filling curves for slow-filling operations.



Time variation of the lock chamber water-surface elevation for these slow-filling operations, Valve Schedules 1 and 2, is illustrated in Figure 45. The computed filling curves (Figure 45) show that the lock filled in 14.7 min with Valve Schedule 1 and 18.9 min with the Valve Schedule 2. Although these valve schedules required longer filling times than when a normal 2 min valve operation is used (8.4 min, Figure 16), this slow-filling operation results in the partially opened valves being subjected to larger discharges than during a 2 min valve operation. The computed time-varying discharges for these two valve schedules are plotted in Figure 46. The discharge differences are attributed to inertia effects. Inertia effectively results in a portion of the head being used to accelerate the mass of water in the culvert. Valve Schedule 1, in which the valves were raised to 50% open, resulted in a peak discharge of 3740 cfs per culvert. The peak discharge was less when the valves were raised to 40% open in Valve Schedule 2. The peak discharge was 2900 cfs per culvert when the valves were held 40% open.

Figure 46. Discharge during slow-filling operations.



Additional experiments were conducted to measure the hoist forces that were generated at the peak discharges of the two slow-filling valve schedules. Forces were measured with the valve held at the 40% (5.6 ft) opening and at the 50% (7.0 ft) opening. Two particular valve designs were evaluated: the existing (Type 5, double-skin-plate) valve and the recommended (Type 7, vertical-frame) valve design. The peak discharges and hoist loads associated with the valves held at the 5.6 ft and 7.0 ft open position are listed in Table 12.

Table 12. Hoist loads, Valve Schedules 1 and 2, Type 5 and Type 7 valves.

Valve Design	Valve Opening, ft	Dry Valve Load, kips	Culvert Discharge, cfs	Total Hoist Load, kips			
				Minimum	Maximum	Load Variation	Observed Average
Type 5	5.6	41.2	2,900	31.7	32.6	0.9	32.1
	7.0	46.8	3,740	32.3	34.7	2.4	33.5
Type 7	5.6	33.8	2,900	27.4	28.1	0.7	27.7
	7.0	37.8	3,740	26.3	27.8	1.5	27.1

Note: Energy elevation immediately upstream from the culvert valve was maintained at approximately el 200. Hydraulic load equals total hoist load less load due to dry weight of the valve.

The hoist load for each valve was not significantly different when the valves were 5.6 ft or 7.0 ft open. The difference in the hoist loads between the two valve designs was primarily due to weight differences. Load fluctuations, which can indicate vibration potential, were similar for the two valve designs at the 5.6 ft opening. However, hoist loads with the Type 5 (double-skin plate) valve varied 2.4 kips at the 7.0 ft opening as compared to 1.5 kips with the Type 7 valve. These data suggest that the Type 7 valve is less susceptible to vibration (hoist-load fluctuations) than the valves originally installed on the Eisenhower and Snell Locks (Type 5, double-skin plate).

3.9 Trunnion forces

Toward the end of the study, trunnion forces were measured for the existing (Type 5, double-skin-plate) and recommended (Type 7, vertical-frame) valve designs to ensure that the new valve would not result in adverse loads on the trunnion. These experiments were conducted with the flow conditions associated with a 2 min valve schedule. The results of the trunnion force measurements with the Type 5 valve are provided in Table 13 and on the graphs in Figure 47–49. The greatest forces exerted on the trunnion occurred at the smaller valve openings. Larger valve openings led to smaller forces on the trunnion. Horizontal forces on the trunnion decreased as the valve opened, and the valve area projected into the flow decreased (Figure 47). The vertical forces on the trunnion of the Type 5 (double-skin plate) valve reduced as the valve opening increased to the 9.0 ft opening (Figure 48). The vertical trunnion loads increased as the valve was raised to the 12.5 ft opening and to the full-open position (Figure 48). The resultant force acting on the Type 5 valve trunnion is plotted in Figure 49.

Table 13. Trunnion loads, Type 5 valve, 2 min valve schedule.

Valve Opening, ft	Culvert Discharge, cfs	Horizontal Force on each Trunnion, kips			Vertical Force on each Trunnion, kips		
		Minimum	Maximum	Observed Average	Minimum	Maximum	Observed Average
1.2	630	85.0	90.8	87.9	24.6	26.8	25.8
2.6	1,280	58.2	61.3	59.7	19.7	21.4	20.7
5.6	2,740	55.3	59.7	57.5	10.7	12.8	11.8
9.0	4,770	30.7	35.5	33.0	1.7	3.9	2.9
12.5	7,090	8.4	14.8	11.1	6.2	9.1	7.8
14.2	7,440	1.5	6.9	3.5	7.9	10.6	9.4

Note: Energy elevation immediately upstream from the culvert valve was maintained at approximately el 200.

Figure 47. Horizontal force on each trunnion, Type 5 (double-skin-plate) valve, 2 min valve schedule.

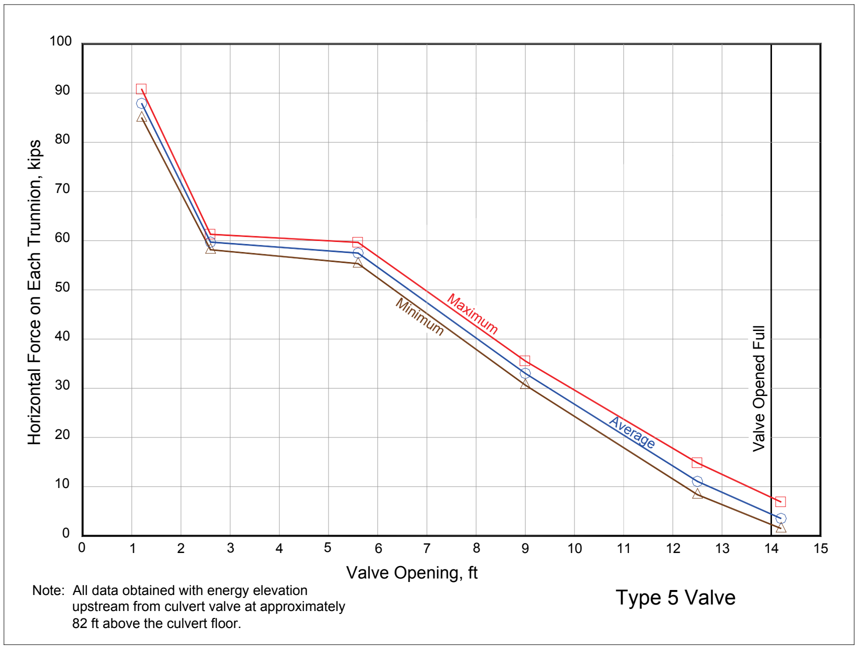


Figure 48. Vertical force on each trunnion, Type 5 (double-skin-plate) valve, 2 min valve schedule.

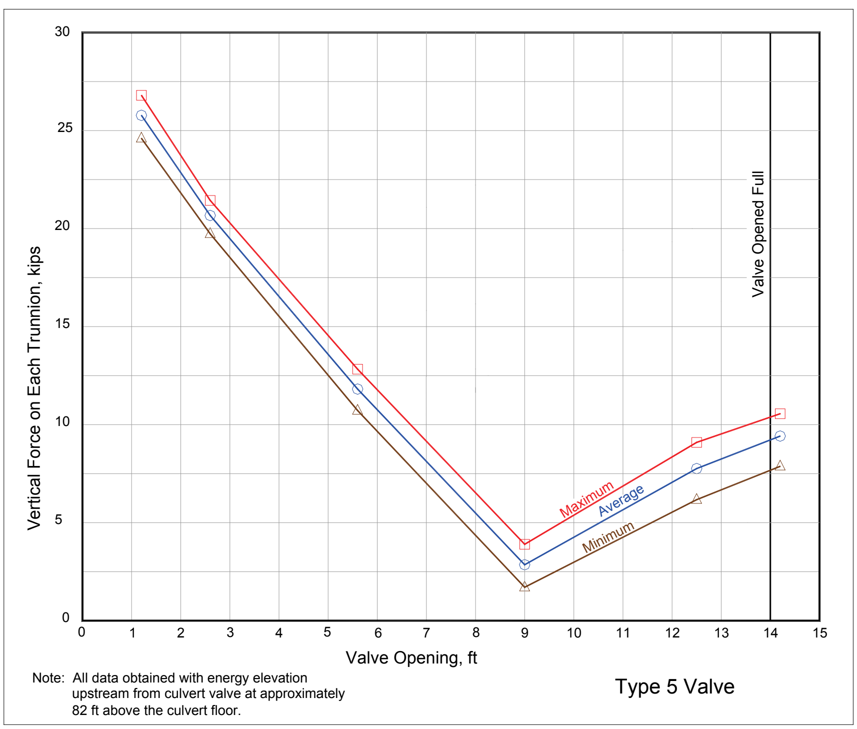
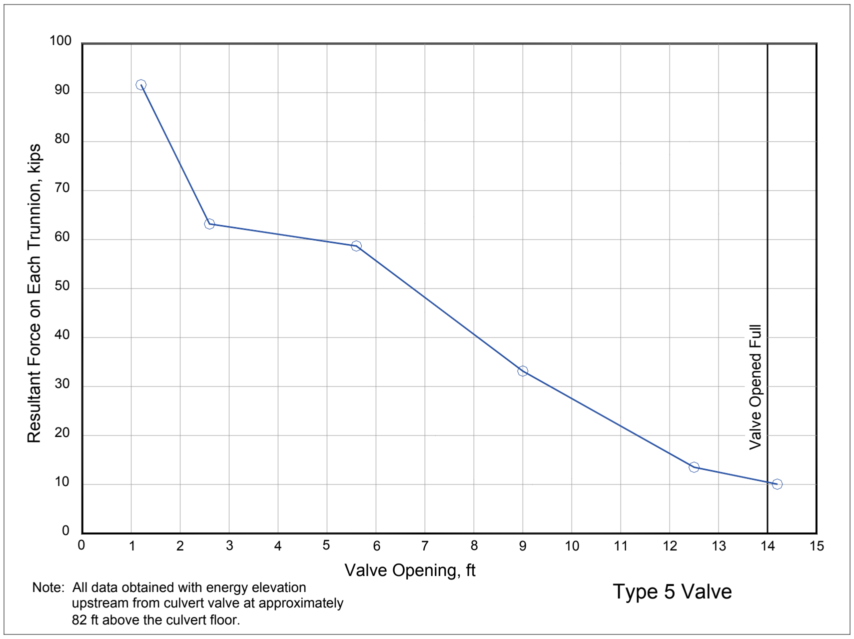


Figure 49. Resultant force on each trunnion, Type 5 (double-skin-plate) valve, 2 min valve schedule.



Trunnion forces with the recommended Type 7 (vertical-frame) valve are provided in Table 14 and are plotted in Figure 50–52. The horizontal forces with the Type 7 valve (Figure 50) were significantly less than those with the Type 5 valve. The vertical forces slightly decreased as the valve opening increased (Figure 51). The resultant trunnion force decreased as the valve opening increased (Figure 52).

Table 14. Trunnion loads, Type 7 valve, 2 min valve schedule.

Valve Opening, ft	Culvert Discharge, cfs	Horizontal Force on each Trunnion, kips			Vertical Force on each Trunnion, kips		
		Minimum	Maximum	Observed Average	Minimum	Maximum	Observed Average
1.2	630	44.5	48.7	46.8	18.4	22.5	20.8
2.6	1,280	28.4	31.5	29.9	14.0	16.0	15.1
5.6	2,740	21.9	26.0	24.0	11.1	13.3	12.3
9.0	4,770	7.8	12.8	10.3	8.5	11.3	10.0
12.5	7,090	3.0	7.0	4.8	6.9	10.3	8.7
14.2	7,440	-1.3	1.9	0.1	7.5	11.3	9.5

Note: Energy elevation immediately upstream from the culvert valve was maintained at approximately el 200.

Figure 50. Horizontal force on each trunnion, Type 7 (recommended) valve, 2 min valve schedule.

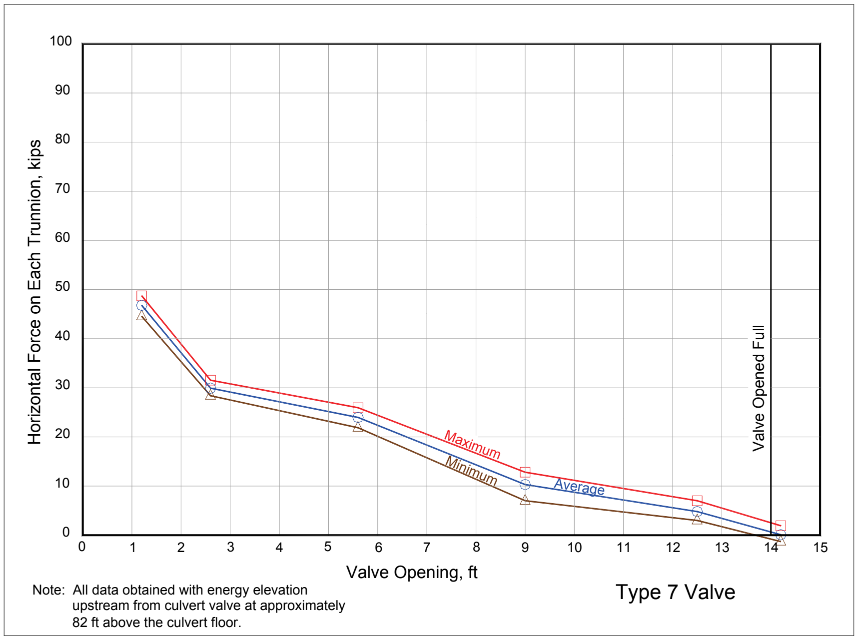


Figure 51. Vertical force on each trunnion, Type 7 (recommended) valve, 2 min valve schedule.

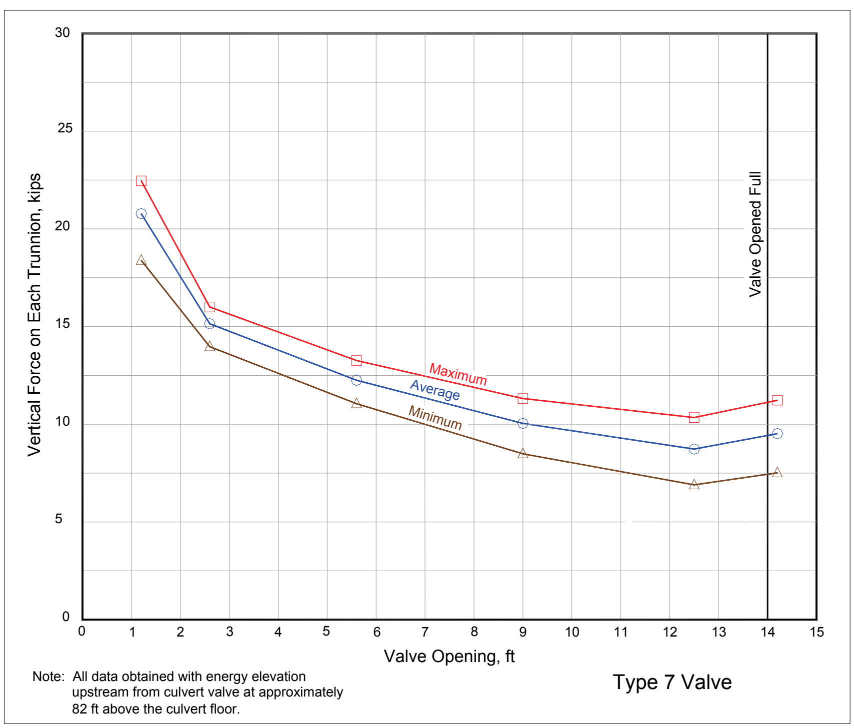
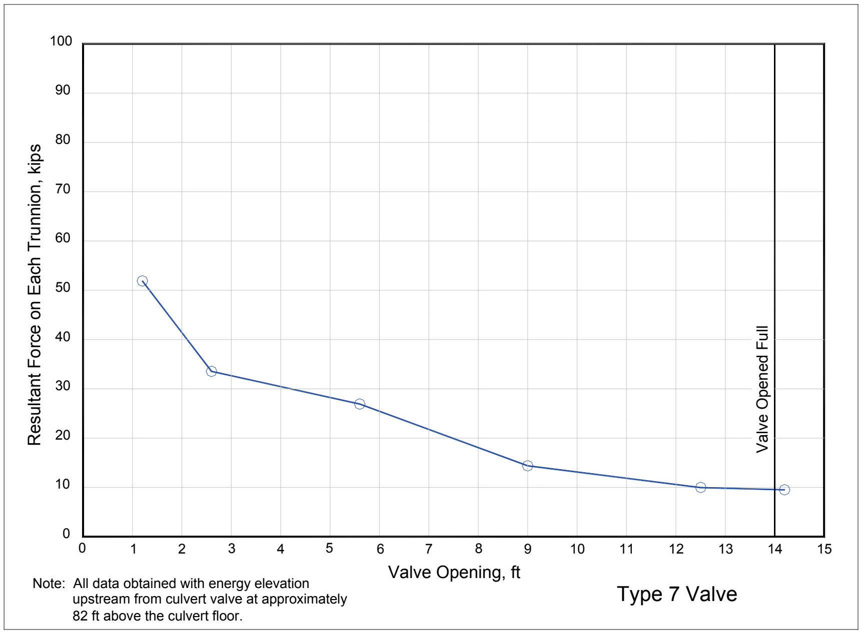


Figure 52. Resultant force on each trunnion, Type 7 (recommended) valve, 2 min valve schedule.



4 Discussion of Experiment Results

Hoist loads were measured with the valve held at particular openings (Figure 14). Culvert discharges associated with a 49 ft lift and a 2 min valve schedule varied with the valve openings. Comparisons of hydraulic load and hoist load data for each valve design tested are presented in Figure 53 and Figure 54, respectively.

Experiments indicated that average hoist loads with the Type 1 (original) valve (Figure 5) varied from approximately 26 kips at an opening of 1.2 ft to approximately 39 kips at an opening of 9.0 ft (Figure 19). Load variations became noticeable at a 9.0 ft opening and increased to a maximum of approximately 16 kips at a 12.5 ft opening. When suspended in the dry, the Type 1 valve exerted loads on the hoist varying from approximately 30 kips near the closed position to approximately 41 kips at the open position. Under normal operating conditions, instantaneous loads on the hoist could be expected to vary as much as 14 kips when the valve was fully open.

Figure 53. Hydraulic load, each valve design tested, 2 min valve schedule.

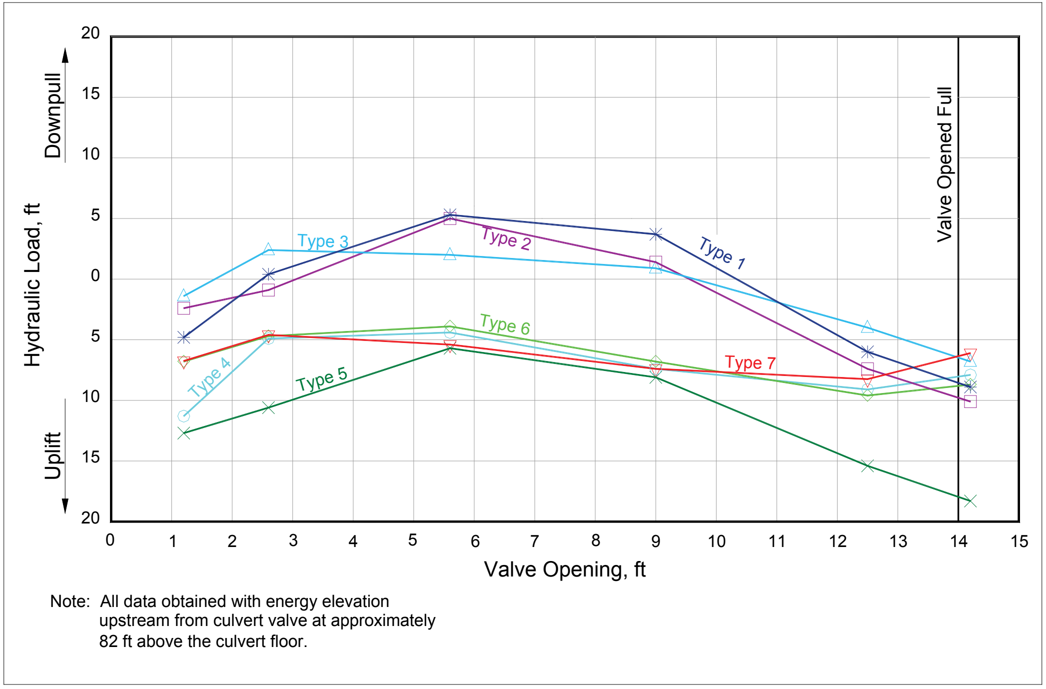
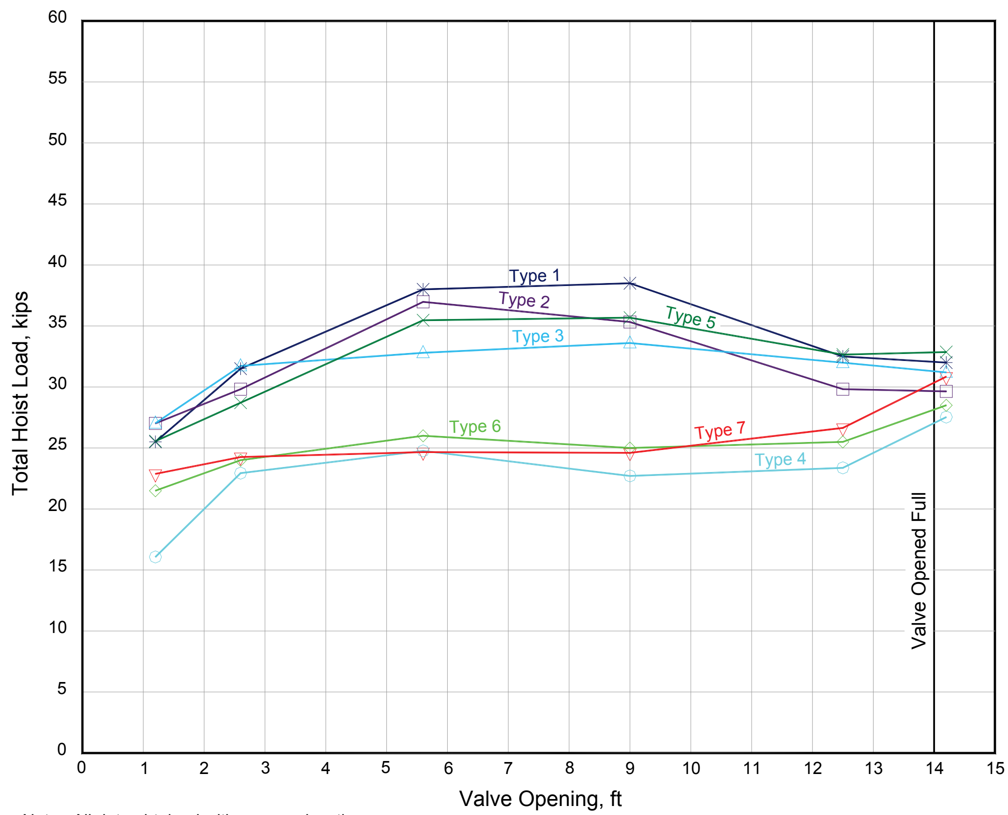


Figure 54. Hoist load, each valve design tested, 2 min valve schedule.



Note: All data obtained with energy elevation upstream from culvert valve at approximately 82 ft above the culvert floor.

Removal of flow obstructions at the ribs reduced hoist loads. The stiffener plates were initially removed (Type 2 valve), and the hoist loads reduced 4 kips at a 9.0 ft valve opening. Removal of the top plate (Type 3 valve) led to additional hoist load reductions. The valve design with no flow obstructions next to the skin plate (Type 4 valve) had the smallest hoist loads of any of the vertical-frame valves tested. Compared to the Type 1 (original) valve, hoist loads were reduced at all valve openings, with a maximum reduction of 15 kips at a 9.0 ft opening. However, the Type 4 valve was not practical for use at the Eisenhower and Snell Locks because the top plate served as bases for appurtenances, and the lack of a bottom seal meant that the valve would not reach the invert when fully lowered.

A vertical-frame valve with only the portions of the top plate required for structural and functional integrity (Type 6 valve) was found to have hoist loads of approximately 25 kips at a 12.5 ft valve opening and 28 kips when the valve was fully open. The Type 6 valve had a maximum hoist load at an

opening of 9.0 ft, which was 13 kips less than the Type 1 (original) valve. Additionally, the hydraulic loads were uplift at each valve position.

The Type 6 valve was not a viable design solution because removal of the bottom seal resulted in a valve that did not seal upon closure. However, experiments with the Type 6 valve served to establish the effects of modifying the top, bottom, and stiffener plates.

Double-skin-plate valves have served as the lock systems' flow controls since the locks were first constructed. Hydraulic loads on the double-skin-plate valve (Type 5 valve, Figure 33) were uplift throughout the operating cycle. The average hoist load varied from approximately 26 kips at an opening of 1.2 ft to approximately 36 kips at openings between 5.6 ft and 9.0 ft.

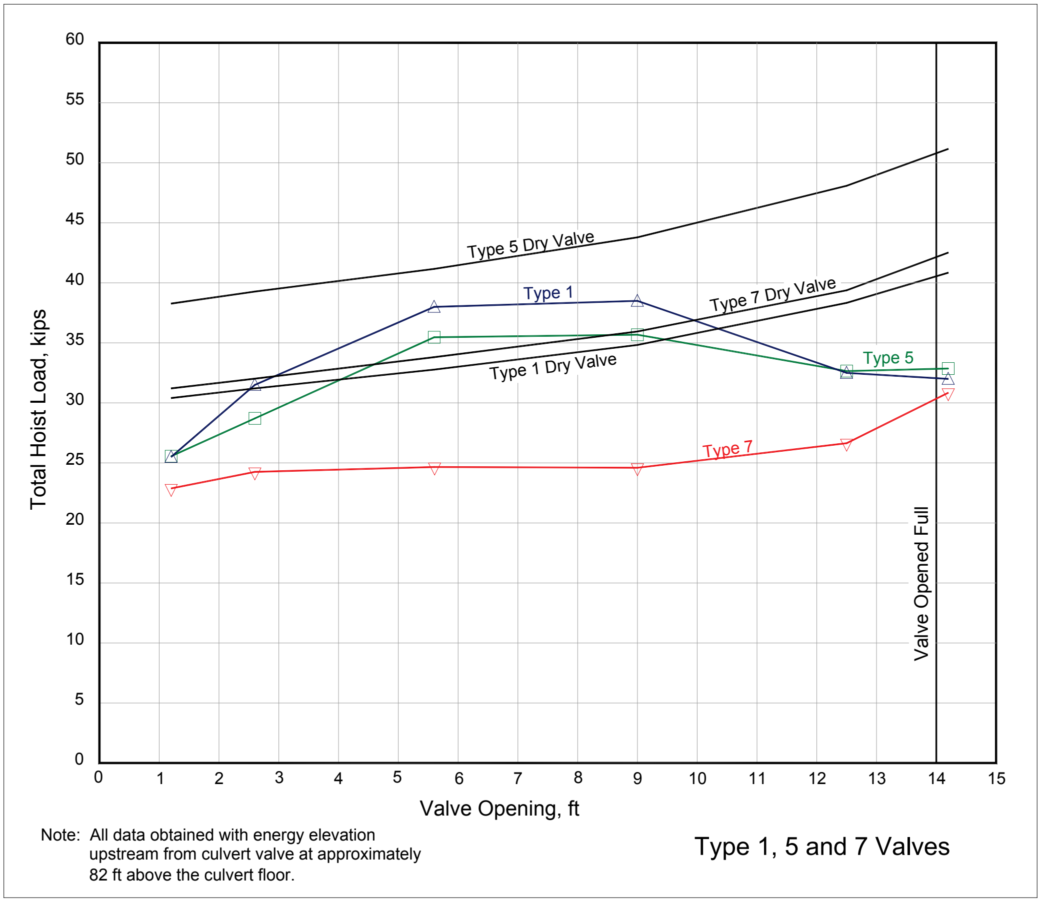
Comparison of the hoist load data for the various designs tested led to the conclusion that, although the double-skin-plate valve was significantly heavier, the operating hoist loads were less than those for the vertical-frame valves. The double-skin-plate valve had more hydraulic uplift force (hoist load minus dry load) than the vertical-frame valve. The uplift forces were most likely generated by low pressures on the top of the skin-wrapped arms and face.

The Type 5 valve had the most uplift, as shown on the plots of hydraulic forces in Figure 53. The hoist forces plotted in Figure 54 show that the Type 7 valve experienced approximately the same force as the Type 6 design, since neither had stiffener plates or bottom plates, and both generally had the same top plate configuration. The Type 4 design, which had no top, bottom, or stiffener plates, had the smallest hoist forces throughout the range of valve openings.

The Type 7 valve (Figure 40) was a new design that incorporated the findings of the first five vertical-frame valve designs. The valve was designed specifically to have minimum flow obstructions across the ribs. The valve had a sharp-lip seal at the lower edge of the skin plate, in accordance with USACE guidance in EM 1110-2-1610 (Headquarters USACE 1975). Hoist loads with the Type 7 valve were approximately 27 kips at a 12.5 ft valve opening and 31 kips when the valve was fully open (Figure 42). This was only 3 kips more than the largest hoist loads measured with the Type 6 valve.

Three valve designs (Type 1, 5, and 7) were specifically designed to fit the Eisenhower and Snell Locks. The other valve designs (Types 2–4 and 6) were modifications of the original vertical-frame valve. Comparison of the hoist forces required for the Type 1, 5, and 7 valve designs to operate during a 2 min valve schedule are shown in Figure 55. The Type 7 valve required the smallest hoist loads of these three designs.

Figure 55. Hoist load, comparison of Type 1 (original) vertical-frame, Type 5 (existing) double-skin-plate, and Type 7 (recommended) valve designs, 2 min valve schedule.



Additional tests were conducted to evaluate conditions when the locks are slowly filled by partially opening the fill valves (Figure 45). The total hoist loads with the Type 7 valve were less than those with the Type 5 valve for both of the slow-filling flow conditions tested. Total hoist load variations are an indicator of vibration potential. The differences between maximum and minimum hoist loads with the slow-filling flow conditions were also less with the Type 7 valve than with the Type 5 valve. This suggested that the Type 7 valve was less susceptible to vibration.

Measurement of the forces acting on the trunnion of the Type 5 and Type 7 valves found that the Type 7 valve forces were significantly less than those with the Type 5 valve (Figure 47–Figure 52). Generally, the vertical forces decreased as the valve opening increased. The horizontal trunnion force decreased as the valve opening increased and the valve area projected into the flow decreased.

5 Summary and Recommendations

The aged double-skin-plate valves of the Eisenhower and Snell Locks on the St. Lawrence Seaway are being replaced. The replacement valves are of the vertical-frame design to facilitate inspection and spot repair. A new vertical-frame valve (Type 1 valve) was installed in the filling valve well of the Snell Lock's south-wall culvert. The new vertical-frame valve operated at a slower rate than the double-skin-plate valve (Type 5 valve), and its operation required more energy. These differences are a major concern in part because the valve operating mechanisms of both locks are being changed from electro-mechanical to an oil-piston configuration. The new system was not designed to lift the additional hoist loads that the vertical-frame valve was apparently requiring.

A physical model study was conducted to identify modifications that could be made to reduce the energy required to operate the new valve. Seven valve designs were evaluated. Six valve configurations were vertically framed with T-beams separating the skin plate from the main horizontal girders. The other valve evaluated was the double-skin-plate design that is being replaced by vertical-frame valves. Judgment of hydraulic performance was based on the hoist loads measured with each valve design.

Physical model experiments found that hoist forces were reduced when lateral plates were removed. The valve design that had no top, bottom, or stiffener plates (Type 4 valve) had the smallest hoist forces. However, this design was not practical because portions of the top plate are required to serve as a base for valve appurtenances.

So, a new design was developed by SLSDC for evaluation in the physical model. The new vertical-frame valve design was designated the Type 7 valve. The design had a top plate that was only large enough to serve as a base for the stabilizers and strut connector. The bottom plate and bottom seal was replaced with a sharp-edged lip formed at the bottom end of the ribs and skin plate.

Model experiments found that the Type 7 valve hoist loads were less than either of the valves currently in operation on the Eisenhower and Snell Locks (Types 1 and 5). The hoist forces generated with the Types 1, 5, and 7

valves are compared using the graph in Figure 55. The Type 7 valve design should not require an excessive amount of energy to operate, as shown on the hoist force graph.

The differences between maximum and minimum hoist loads with the slow-filling flow conditions were also less with the Type 7 valve than with the Type 5 valve. This suggested that the Type 7 valve was less susceptible to vibration.

The Type 7 valve is the recommended design because it was specifically designed to fit the Eisenhower and Snell Locks. The valve meets the USACE guidance for vertical-frame valves (including the lip shape), and it has hoist forces that are lower than the valves currently in operation (Types 1 and 5).

The Type 7 valve design should provide acceptable performance when used for any of the filling or emptying valves on the Eisenhower or Snell Locks. The Type 7 valve is recommended for replacement of the double-skin-plate valves. Furthermore, if cost allows, the one vertical-frame valve, which is in operation on the Snell Lock's south-wall filling culvert (Type 1 valve), should be replaced with a new valve fabricated to the Type 7 design. If replacement of the Type 1 valve is currently cost prohibitive, removal of the stiffener plates (resulting in a Type 2 valve) would improve valve performance. The bottom plate cannot be removed because it supports the seal, and removal would mean that the valve lip would not reach the invert when fully lowered.

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14. ABSTRACT

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A physical model study was conducted to identify modifications that could be made to reduce the energy required to operate the new valve. The recommended valve design had a top plate that was only large enough to serve as a base for the stabilizers and strut connector. The bottom plate and bottom seal was replaced with a sharp-edged lip formed at the bottom end of the ribs and skin plate. The recommended valve was specifically designed to fit the Eisenhower and Snell Locks, it meets the USACE guidance for vertical-frame valves, and it had hoist forces that were lower than the valves currently in operation.

15. SUBJECT TERMS

Double-skin-plate valve
Eisenhower and Snell Locks
St. Lawrence Seaway
Vertical-frame valve

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